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Design and Development of a Testbed Prototype for Cognitive Radio Transmission over TV White Space

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By

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Design and Development of a Testbed Prototype for Cognitive Radio Transmission over TV White Space

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DECLARATION OF CO-AUTHORSHIP AND PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows: Chapter 3 and 4 of the thesis was co-authored with Danilo Corral-De-Witt, Sabbir Ahmed under the supervision of professor Kemal Tepe. In all cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by the author. Dewan Md Ariful Hassan contributed to the background study, Hypothesis modelling, Hardware Setup, Data Collections; Danilo CorralDe-Witt, and Sabbir Ahmed provided feedback on refinement of ideas and editing of the final manuscript. Some Parts of the Chapter 3 are included in a paper co-authored by Danilo Corral-De-Witt, Aarron Younan, Dewan Ariful, Lining Zhang, under the supervision of professor Kemal Tepe. Danilo Corral-De-Witt primary contributed, experimental designs and hardware setup; Aarron Younan provided the energy detection algorithm and Lining supported writing and reviewed the paper. I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis. I certify that, with the above qualification, this thesis, and the research to iii which it refers, is the product of my own work.

II. Previous Publication This thesis includes [2] original papers that have been previously published for publication in peer reviewed international conferences, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Part of Chapter 3 & 4	1. Dewan Md. Ariful Hassan, Danilo Corral-De-Witt, Sabbir Ahmed and Kemal Tepe, “Narrowband Data Transmission in TV White Space: An Experimental Performance Analysis” has been accepted on IEEE International Symposium on Signal Processing and Information Technology, Louisville, Kentucky, USA, 2018.	Published
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ABSTRACT

Considering the ever-increasing demand and the associated high costs of wireless electromagnetic spectrum, technologies that can facilitate efficient spectrum utilization are of utmost importance. Cognitive radio (CR), in conjunction with TV White Spaces (TVWS), can be a viable solution, where unlicensed or secondary users can opportunistically use the not-currently-in-use, aka idle, TV channels registered to licensed or primary users. This thesis focuses on the design and development of a testbed prototype for real-time testing of secondary user transmission in TVWS. Once an unused TV channel has been identified, our system uses that idle channel for transmitting and receiving signals. The testbed is built on Universal Software Radio Peripheral (USRP) device powered by GNU Radio Software, Software Defined Radio (SDR) receptor, and Spectrum Analyser. The developed prototype splits a given TVWS channel into multiple small sub-channels and performs channel characterization through end-to-end transmission and reception of information carrying signals. The channel characteristics are presented through Bit Transfer Rate (BTR) and frequency spectrum results. The prototype also facilitates provisions for applying error correction coding as a mean of undertaking comparative performance testing.

DEDICATION

I dedicated this thesis to my Mother and Father who spent their life on educating science to me. They always have encouraged me to continue my education on the Master of Science in Engineering. I am very thankful for their support, patience, and encouragement during my research.

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A special thanks go to Dr. Sabbir Ahmed, and Mr. Danilo Corral De Witt they have been the vital support throughout my work. Finally, my deepest gratitude goes to my family and friends for their unconditional love and support throughout my life and my studies.

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LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
BAS	Broadcast Auxiliary Services
BTR	Bit Transfer Rate
CVSD	Continuously Variable Scope Delta
CREATE	Cognitive Radio Networking Architecture
CPC	Client Procedures Circulars
CAGR	Compound Annual Growth Rate
CR	Cognitive Radio
DTV	Digital Television
dB	Decibels
EIRP	Effective Isotropic Radiated Power
FFT	Fast Fourier Transform
FEC	Forward error correction
FCC	U.S. Federal Communications Commission
GHz	Gigahertz (1 GHz = 10^9 hertz or a frequency of one billion cycles per second)
GUI	Graphical User Interface
GRC	GNU Radio Companion
LPA	Low-power apparatus (e.g. wireless microphones)
MHz	Megahertz (1 MHz = 10^6 hertz or a frequency of one million cycles per second)

M2M	Machine to Machine
PU	Primary user
PR	Received Power
QoS	Quality of Service
RTL	Register-Transfer Level
RSS	Radio Standards Specifications
SRSP	Standard Radio System Plans
SU	Secondary user
SNR	Signal to Noise Ratio
SDR	Software Defined Radio
TV	Television
TVWS	Television White Space(s)
UHF	Ultra High Frequency
USRP	Universal Serial Radio Peripheral
VHF	Very high frequency
Wi-Fi	Wireless Fidelity, an industry technical standard for wireless networking
WiCIP	Wireless Communication and Information Processing lab
WSDB	White Space Database

CHAPTER I

INTRODUCTIONS

1.1 Background

Communication has always been one of the most profound needs throughout the history of human civilization. Communication technology innovation has seen the subsequent emergence of telegraphy, telephony, video, computer communication. Moreover, nowadays, the astounding blend of these technologies are integrated into cheap, versatile gadgets. The main backbone of a modern communication system is Digital communication as illustrated in Figure 1.1.

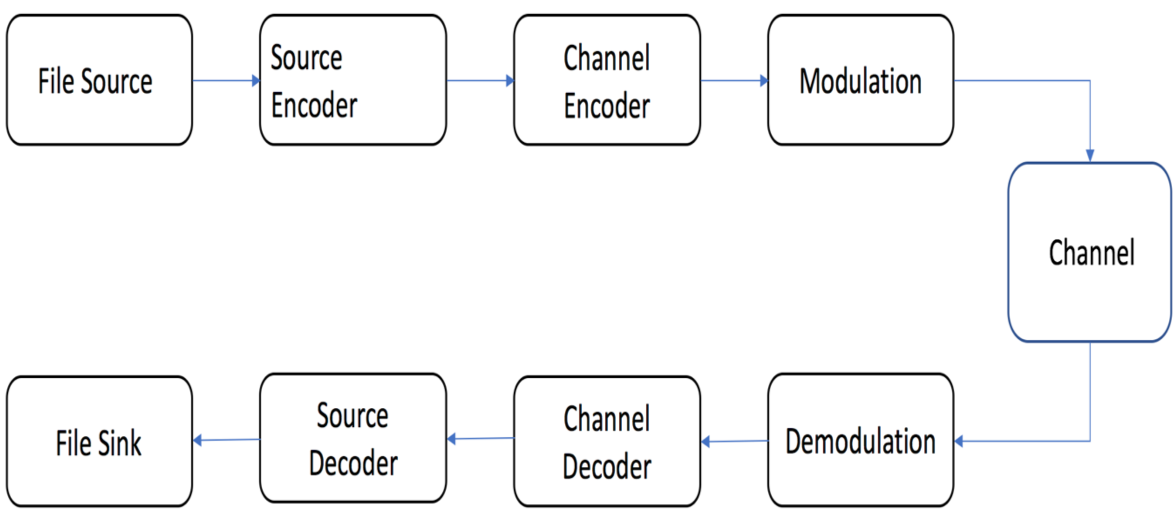


Figure 1.1 Basic Information Processing System.

In the figure, source information is processed through a system to encode and modulate the data for transmitting. The encoding system output is then transmitted via a particular physical communication channel. The channel decoder (demodulator) reproduces the approaching binary sequence, and the source decoder reproduces the source signal.

Nowadays, consumers are demanding more from wireless communications systems. According to Cisco's forecast internationally, devices and wireless connection are developing faster (10% Compound Annual Growth Rate (CAGR)) than both the population (1.0% CAGR) and Internet users (7% CAGR). Every year, different new devices in various frame factors with expanded abilities and insight are presented and embraced in the market. A developing number of Machine to Machine (M2M) applications, for example, smart meters, video surveillance, healthcare observing, transportation, and asset tracking, are contributing significantly to the development of gadgets and connections. By 2022, M2M devices will be 51% of the total invention and connections. M2M connections will be the fastest developing class at 19% CAGR, to 14.6 billion connections by 2022. Cell phones will become the second fastest at a 9% CAGR (expanding by a factor of 1.6). Smart TVs will develop the next fastest at 7% CAGR, to 3.2 billion by 2022. However, the wireless network capacity cannot keep up with the explosive growth in data traffic [1]. This is why a better utilization of the available spectrum is, and this thesis will target to increase spectrum efficiency.

1.2 Motivation

To increase the efficiency of spectrum usage, TV White Space (TVWS) with Cognitive Radio (CR) can be a good choice. CR system with TVWS can offer many useful applications and services. Some of them are listed below.

Communication in Emergency Management:

We often find that communication system physical infrastructure gets severely affected during natural calamities like earthquake, tsunami, typhoon, flood, etc. But for proper rescue and post-disaster management, communication is vital. It is possible to provide live two-way voice and data wireless communications using TVWS [3]. In these situations, the CR system can be advantageous because of quick and affordable deployment. Moreover, a rescue robot could be used to disaster relief operations works in a prohibited entry area [4].

Internet of Every Things (IoE):

Figure 1.2 Internet of Everything.

The idea of the Internet of Everything started at Cisco, who characterizes IoE in Figure 1.2 as "the keen association of individuals, process, information, and things." Because on the Internet of Things (IoT), all communications are between machines. IoT is illustrated in Figure 1.3 and M2M are at times thought about synonymous. The more far-reaching IoE idea incorporates, other than M2M interchanges, machine-to-personal (M2P) and innovation helped people to people (P2P) collaborations. TVWS Broadband Remote arrangement given an IP based creative IoT organized spectrum that keeps running over unlicensed television white space TVWS frequencies (470-700MHz). The method requires three principal parts: a) a Cloud-based Server that deals with the System; b) Base Stations that disseminate and gather the IP traffic; c) IoT terminals/sensors that transmit/ receive the data at the system edges.

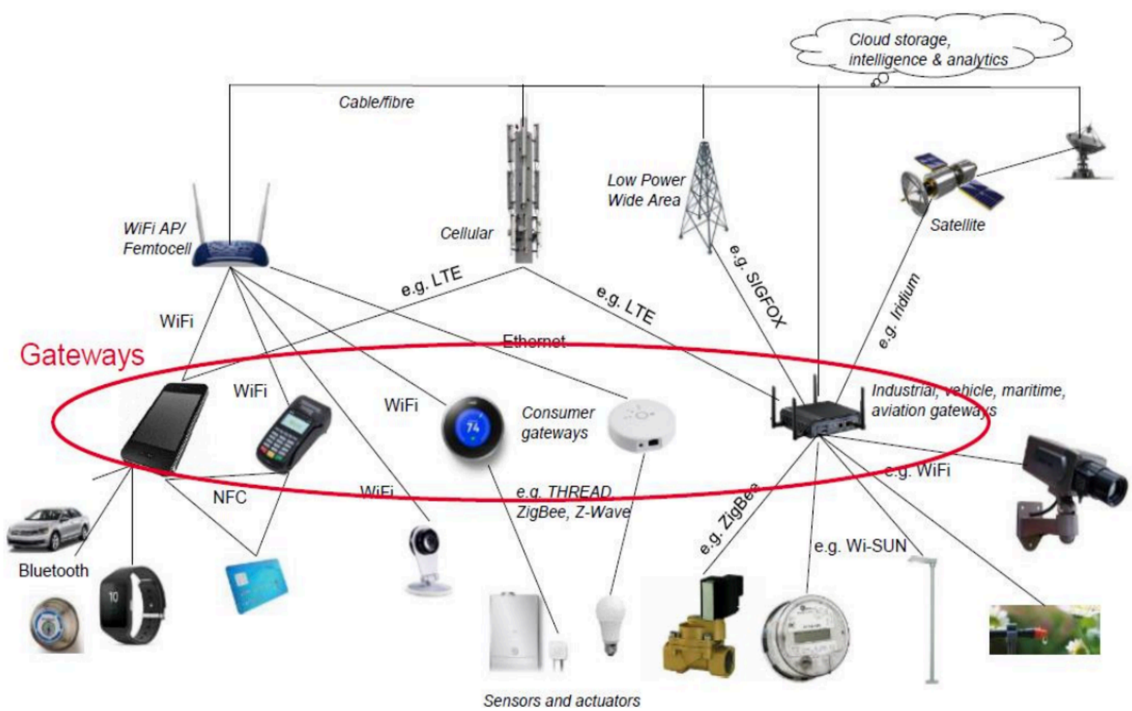


Figure 1.3 Connecting Things in M2M / IoT.

End to End IoE System that will have the capacity to communicate and get information from different sensors in remote Non-Line of Side (NLOS) areas at TVWS that is free for applications like IoT and others in numerous spots everywhere throughout the world like the US, UK and Singapore and in the procedure to be open in different nations of the globe [5].

White Space Internet Connection in Rural or Remote Area:

We are progressively focusing on the Internet for communication, data, health services administrations, instruction, business relations, and disaster management. Internet must be viewed as an essential human right in days to turn out of 7.2 billion total populations, just 3.3 billion people are associated through Internet Wireless Technology. The network is an absolute necessity for the country zone to oversee restricted assets and use them in a productive way like power, water system, etc. [6].

Super Wi-Fi:

The TV White Space innovation is additionally called Super Wi-Fi as its range is substantially more contrasted with typical Wi-Fi (Table 1.1).

Table 1.1: Showing the comparison between TVWS, Cellular, Wi-Fi & ZigBee.

Parameter	TVWS	Cellular	Wi-Fi	ZigBee
Cost	Low	Recurrent	Low	Low
Coverage	Large	Large	Small	Small
Latency	Low	High	Low	Medium
Power Consumption	Medium	High	High	Low

As per Carlson Technologies, while Wi-Fi covers a couple of feet, Super Wi-Fi can cover a length of 10-KM [7]. This is more than multiple times the range than typical Wi-Fi can go. The significant issues with standard Wi-Fi are that it turned out to be frail with space voyage and can't pass deterrents so they can't be utilized in sloping territories. Super Wi-Fi has better range and coverage.

As described above, the CR system in TVWS can not only increase spectrum usage efficiency but also offer different services. But it is essential to have a testbed that can be used for testing the CR system. This motivated us to develop a testbed that can be used for transmitting signal in a detected free channel and evaluating the similar channel performance.

1.3 Research Objectives

It is quite evident that the demand for free spectrum is already quite high and it is only going to increase in the days ahead. To satisfy this vast demand CR system can play a significant role by recognizing and accessing unused or free spectrum on the fly. In such an order, primary users share their frequency with unlicensed devices or users, known as secondary users. Idle or not-in-use TV spectrum, better known as TVWS are quite attractive for use in the CR system and has drawn significant research interest [2]. The critical issue is that the interference between the primary user and secondary user should be avoided. Considering the potential of CR system for future generation communication system and associated challenges, the objective of this research are to design and develop a testbed prototype that can facilitate real-time testing of secondary user transmission in TVWS [2].

The Specific Objectives are:

Our overall objective is to exploit the TVWS and measure how well the CR works in TVWS. In particular, we focused on the following activities.

• Building a communication scheme prototype for transmitting data in real-time UHF TV bands using USRP.

• Investigating the performance of the communication scheme and observing the receiving data in the frequency spectrum.

• Measuring the bit transfer rate of the receiver end.

1.4 Thesis Contribution

In this thesis, we demonstrate actual transmission in TVWS without hampering the primary user. For this, we have developed a test prototype. In this prototype, we used spectrum analyzer for sensing the TVWS first. Second, from the spectrum sensing data, we accurately find out the free and the occupied frequency spectrums. For transmitting using the USRP, we implemented different types of modulations schemes, e.g., DPSK, GMSK, etc. using GNU Radio Companion (GRC) Block diagram in GNU Radio. The following activities were performed.

- Discovered different configurations for USRP to send and receive multiple types of file such as text, audio, picture, etc.

- Scanned from the 32 TV channels, only in 23 of them, we detected the presence of a Primary user (PU) and nine were detected as idle channels in the Windsor.
- Real-time transmission in TVWS is successful.
- Configured different types of modulation schemes and performance analysis tools for testing the transmission.
- Gained knowledge about GNU Radio and USRP operation.
- On this research topics two papers accepted in IEEE conference.

1.5 Thesis Outline

This thesis has all together five chapters. They are organized as follows:

Chapter-I presents a brief overview of the thesis works and methods for communications in TVWS as secondary users.

Chapter -II explains the background, TV White Space, IEEE 802.22 stander for TVWS and literature review for the related works.

Chapter-III presents the concepts of the prototype development sub-channel formation for using the TVWS as multiple channels, features of the USRP 2901 and GNU Radio.

Chapter-IV presents a new implementation of using USRP 2901 to make a real-time transmission in TVWS and performance analysis of the system.

Chapter-V presents the conclusion and summarizes the results and future works.

CHAPTER II

RELATED WORKS

2.1 Background

CR is an innovation that can consequently take decisions about its operation and characteristics as per its environment. When we frame the name "cognitive radio" (CR), the best definition in Haykin's words can be quoted as [8],

" *Cognitive Radio is an intelligent wireless communication system that is aware of its surrounding environment and uses the methodology of understanding-by-building to learn from the situation and adapt its internal states to statistical variations in the incoming RF (radio frequency) stimuli by making corresponding changes in specific operating parameters in real-time."*

Thus CR is based on the methodology of humans by understanding, learning and then adapting to the surrounding. There are two main highlighting features of CR:

1) Reliable communications whenever and wherever needed;

2) Efficient utilization of the radio spectrum.

Licensed spectrum: A particular range of frequency band is allocated for specific organizations within the portion of the radio spectrum, and this band is licensed a user by the governmental spectrum management authorities. The license provides the licensee legal protection and enforcement to prevent other operators from transmitting over the same frequency in the same geographic area. In a typical communication system, the user of the licensed band is known as the PU.

Unlicensed Spectrum: The unlicensed spectrum is the portion of radio frequencies have that is not allocated to any particular user. For example, Wi-Fi, The Wi-Fi industry's has conveyed huge advantages to users and driven immense economic value worldwide. The secondary user (SU) is allowed to use the Licensed primary spectrum in case of the first user's absence. SU has the lowest priority regarding spectrum usage. The functionality of a CR is shown in Figure 2.1.

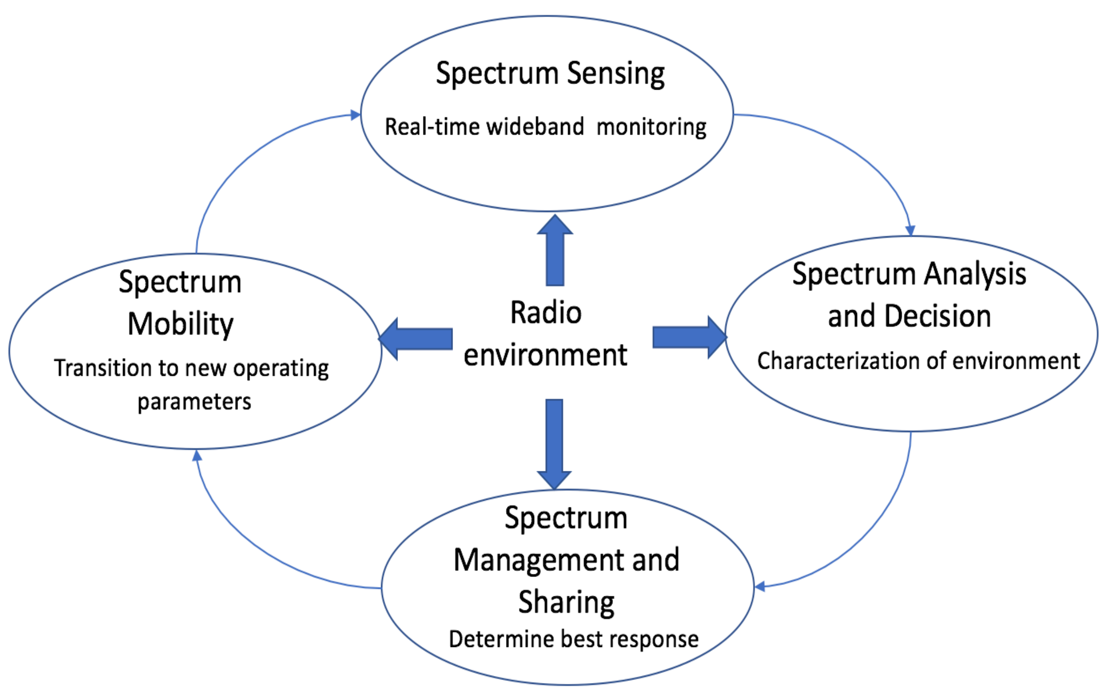


Figure 2.1 Main Functions of CR.

The functional components are:

1. Spectrum sensing - responsible for detecting unused spectrum. To avoid interference, the radio scans the spectrum for free channels. The most efficient way is to identify the primary users of the spectrum.
2. Spectrum management - responsible for capturing the best spectrum available for the required Quality of Service (QoS) of communication. The first analysis is made on the frequency for interference, path loss.
3. Spectrum mobility - responsible for maintaining seamless communication during spectrum transition by using the channel information exchanges.
4. Spectrum sharing - responsible for providing fair spectrum scheduling method for sharing the available open spectrum.

2.2 TV White Space

TVWS are that those TV channels are not being utilized for television broadcasting in specific areas consistently. A television Radio Frequency (RF) channel is allocated 6 MHz of bandwidth and the spectrum range of 470-890 MHz (ITU- Region 3 Frequency Allocations). Television stations are often operated in geographically different locations, to avoid interference between each other, and other reasons, not all television channels are utilized. The available spectrum in the form of TVWS can fluctuate rely upon different factors which are given below:

i) Frequency: Unused channels of a TV band plan in some geographical areas due to interference avoidance techniques like employing guard bands,

ii) Height: the accessibility of TVWS depends on the height of the TVWS transmission site and its antenna height.

iii) Space: No broadcasting signal is currently present outside of the TV coverage areas.

iv) Time period: TV stations are not using the assigned frequency bands for a specific period, so making it available for use as TVWS on a non-interference basis.

According to Industry Canada, TVWS devices be permitted to operate on available channels throughout the TV broadcasting bands below 698 MHz.

Table 2.1: Available Channels by Type of WSD [9]

Frequency Bands (MHz)	TV Channels	Personal/Portable WSD	Fixed WSD
54-60	2	Not permitted	√
60-72	3-4 *	Not permitted	Not permitted
76-88	5-6	Not permitted	√
174-216	7-13	Not permitted	√
470-512	14-20	Not permitted	√
512-608	21-36	√	√
608-614	37 **	Not permitted	Not permitted
614-698	38-51	√	√

2.3 The IEEE 802.22 Standard

The IEEE 802.22 standard defines a system for a Wireless Regional Area Network, to deal with the white spaces present in the TV spectrum, it allows secondary user to use TV bands between 54 and 862 MHz. The 802.22 standard goal is to protect the TV service that there is no interference happening in TV broadcasting. As a result of the fact that 802.22 uses cognitive radio technology [10].

The IEEE 802.22 standard should provide extensive usage of broadcast spectrum, high data rate, long range, immunity to interference, and the most of all it can be operated in the licensed as well as an unlicensed band. The operating parameters are provided in Table 2.2.

Table 2.2: IEEE 802.22 standard

PARAMETER	SPECIFICATION
Typical cell radius (km)	30 - 100 km
Methodology	Spectrum sensing to identify free channels
Channel bandwidth (MHz)	6, (7, 8)
Channel capacity	18 Mbps
User capacity	Downlink: 1.5Mbps Uplink: 384 kbps

2.4 Literature Review

We have reviewed six papers relevant to the work to make a communication scheme over TVWS using USRP 2901:

Reference [11] developed an SDR testbed for frequency interference analysis amongst secondary users where the performance of a Zigbee device was investigated under Wi-Fi interference. Measured bit error rate (BER) showed good agreement between theoretical and simulated results. The testbed was built around NI USRP 2922 device and LabView Software. The article does not consider TVWS, which is the focus of this work. In [12], a testbed was developed for real-time interference detection applying signal cancellation technique. The underlying SDR device is NI USRP 2954R, and a channel emulator is used that injects Additive White Gaussian Noise (AWGN) generated by a feedback shift register arrangement. Therefore, as per our understanding, this paper reports a work in which the transmission part is a simulation.

Using USRP N210, [13] reports on BER analysis of Continuously Variable Scope Delta (CVSD) vocoders utilizing GNU Radio. In this paper, two coding plans interface to achieve substantial coding gains with affordable decoding complexity. Two coding organize as Convolutional coding as external code and Reed-Muller coding as the inner code. In the case of BER, they inferred that the CVSD coder with Forward Error Correction Code (FEC) is better than without FEC. This testbed is built for IEEE 802.16e WiMAX specifications. In [14], a Distributed Cognitive Radio Network Architecture made on USRP N210 and GNU radio is proposed. They developed an end-to-end Cognitive Radio

Networking Architecture (CREATE) that deploys spectrum sensing, channel rendezvous, neighborhood discovery, channel estimation for distributed coordination, routing, spectrum allocation, and joint scheduling. This work uses the emulated channel for performance analysis. [15] discusses the capacity of GNU Radio and SDR for developing and testing the wireless system. They claimed to implement the transmitter, receiver, and repeater functionally with three nodes of the USRP. However, there is no data, GRC block or USRP model name that prove how they developed that system; basically, it is just a theory. In [16], a prototype was built using USRP 2901, python application, Arduino-based GPS and UHF antenna for scanning the TV spectrum sensing. This prototype was employed to detect the spectrum in the city of Windsor dynamically; however, they did not mention or put any data regarding which channel is free (TVWS) or not. The novelty of this paper was sampling vs. polling frequencies and the distance between data reading and speed.

To sum up, all these relevant works use the GNU Radio or USRP, and their work includes making testbeds for simulation, spectrum sensing, channel estimation, bit error calculation, etc. As far as our knowledge, nobody has built a prototype with cognitive radio to make a real-time transmission and make a testbed for the TV white spaces.

CHAPTER III

PROTOTYPE DEVELOPMENT

3.1 Introductions:

The primary goal of our work is to demonstrate how real-time transmission can be realized in TVWS and analyze performance. Our prototype has three significant areas which are illustrated in Figure 3.1 and are as follows: 1) sensing for TVWS, 2) make a transmission in TVWS, and 3) analysis the performance of overall communication. After finding the TVWS, we need to decide at which frequency and channels of that TV band are [17].

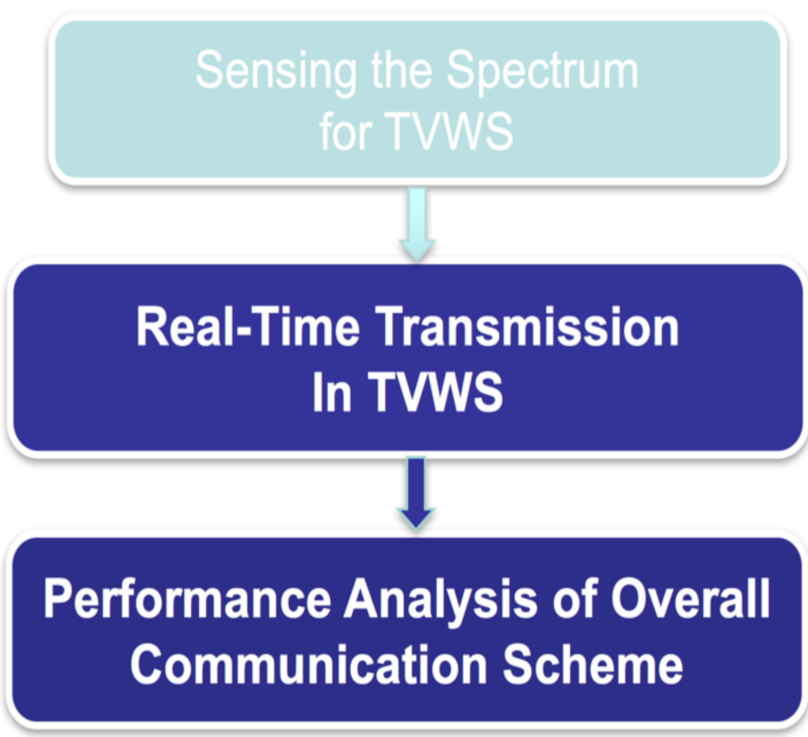


Figure 3.1 Flow graph of the concepts of this prototype.

Then we can establish the connection between two points using transmitter and receiver. After the establishment phase, we tried to calculate the bit transfer rate to understand the performance of the communication system.

3.2 Sub-channel Formation

Our prototype uses an idle TV channel for SU data transmission. In general, the bandwidth of the North American terrestrial TV channels is 6 MHz. A lot of wireless applications do not need such a vast spectrum, e.g., emergency weather alert, V2V or V2I communications, disaster time intra-rescue team voice or data communications, etc. For these types of applications, we considered dividing a single TVWS channel into multiple sub-channels [18]. Figure 3.2 depicts our sub-channels formation strategy.

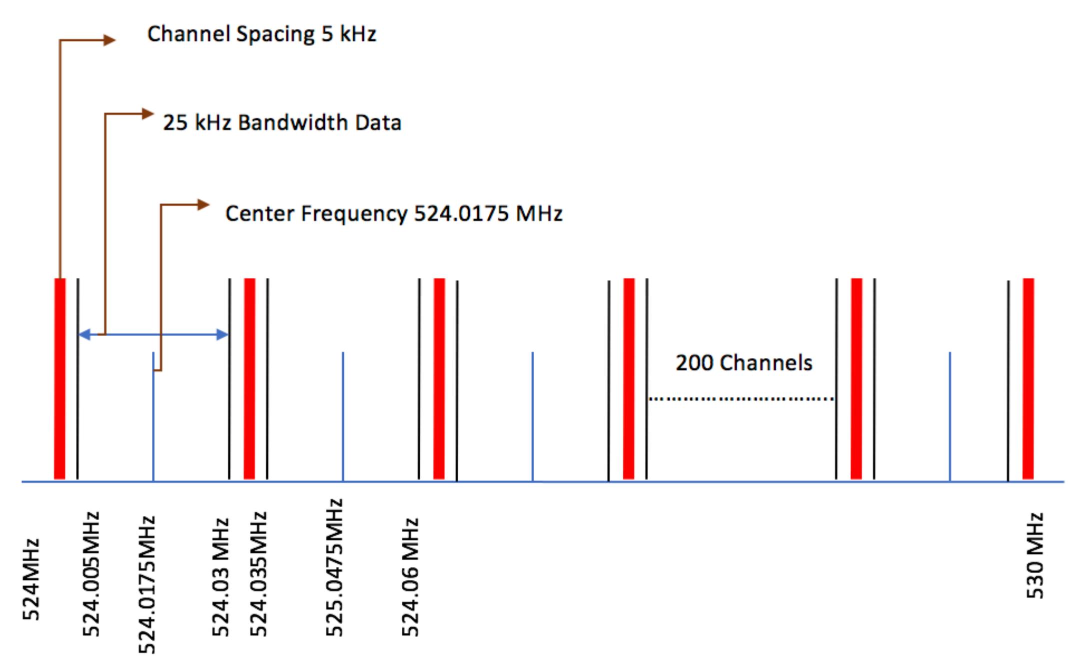


Figure 3.2 Channel 23 TVWS 6 MHz Bandwidth using plan as a secondary user.

Our adopted sub-channel formation scheme considers each sub-channel as a 25 kHz-wide channel having a 5 kHz spacing with the adjacent preceding channel. For example, the channel#23 is a terrestrial TV channel occupying the spectrum range of 524 MHz- 530 MHz. For this channel, when our sub-channel formation proposal is applied, the first sub-channel frequency range is 524.005 MHz - 524.030 MHz with the centre frequency at 524.0175 MHz. In this way, our sub-channel formation can form 200 such sub-channels within channel#23. Such sub-channels can also facilitate opportunistic multicarrier high-speed communications. Now, in a radio link, the Received Power (P_R) in free space model [19] may be defined by:

$$P_R = P_T\, G_T\, G_R\left(\frac{\lambda}{4\pi d}\right)^2 \qquad (1)$$

Where P_T is the transmitted power, G_T and G_R are the gains of the transmitting and receiving antennas, is the wavelength, and d is the distance of the link, if $P_T + G_T \approx$ EIRP, the term $(\lambda/\pi 4d)^2$ corresponds to Free Space Loss (L_{FS}), also may be written as:

$$L_{FS} = 20\,log(d) + 20\,log(f) + 32.45 \qquad (2)$$

where d is given in kilo meters and f in MHz [20].

3.3 System Model

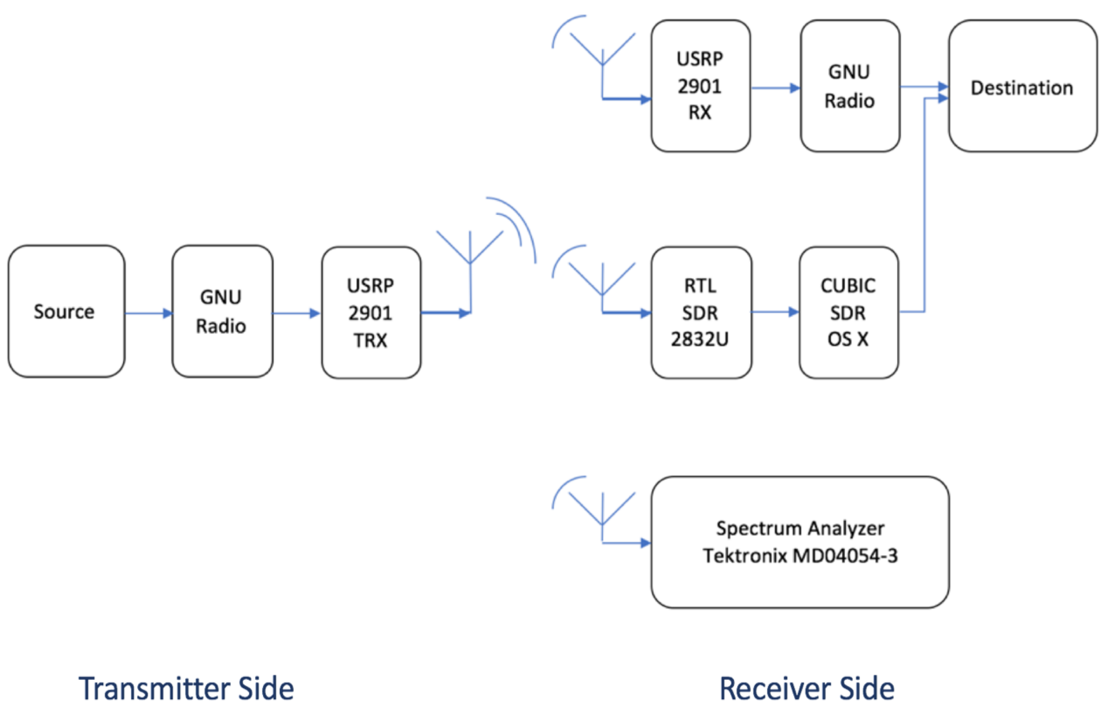


Figure 3.3: System architecture of prototype, transmitter side (left) and receiver side(right).

Figure 3.3 shows the functional model of our system model. For all the three types (text, audio, image) of data that we consider in our work. We design our system in the way that we could do the transmission and reception of data and observe the spectrum simultaneously; this is the unique feature of our system. For communication, we merely need a USRP 2901 [21] and a computer the source of the data are files stored on a desktop computer storage. The transmitter side USRP 2901 device is physically connected to this computer through a USB port. This device performs the actual operation of wireless transmission through the antenna that is connected to it. The GNU Radio software [22] also runs on this computer, and it facilitates all controls and configuration activities for the entire transmission side setup. For example, fetching data from the storage, specifying the parameter of modulation and transmission frequency and bandwidth, executing the transmission process and so forth.

On the receiver side of the system, we design the system in the way a that it is movable. We need one USRP 2901 and one RTL connecting with a laptop; however, we also used a Tektronix MDO4054-3 because its sensitivity is higher than RTL for monitoring the spectrum. There are three different categories of hardware set-ups. Firstly, a USRP 2901 device that acts as the receiver. Through a C port, this USRP device is physically connected to a laptop computer which operates as the final destination of the received data. Similar to the transmitter side, we also run the GNU Radio software on the receiver laptop. Secondly, a spectrum analyzer (Tektronix MDO4054-3) which is used to monitor and analyze the signal spectrum [23]. Finally, as an additional spectrum monitoring and analyzing device, we used an RTL SDR 2832U in conjunction with the same laptop computer that is connected to the USRP device. The RTL device is inexpensive and portable. However, for more precise results, we use the Tektronix MDO4054-3 spectrum analyzer as the third hardware component in the receiver side. For a specified sampling rate, this device shows exquisite sensitivity and has the capability of displaying and storing spectrum-related information.

The salient Hardware and Software used are listed below, and pertinent detail description and specifications follow in the subsequent subsections:

Hardware

- USRP 2901.
- Spectrum Analyser Tektronix MDO4054-3.
- RTL SDR 2832U.
- MacBook Pro, 2GHz Intel Core i5

Software

- macOS High Sierra V10.13.6
- Gnuradio.
- XQuartz 2.7.11 (xorg-server 1.18.4).
- MATLAB Student version 2017.
- CubicSDR v0.2.2- OS X.
- Gqrx Mac OS X 10.11.

RTL SDR 2832U

Figure 3.4 RTL SDR 2832U.

NooElec RTL is a low-cost (Figure 3.4), portable SDR device that can be operated on different types of OS platform, e.g., OS10, Windows 32 & 64 bit, MacOS, Linux, etc. It comes with Tuner IC R820T2 and USB Interface IC RTL2832U. In our work, we fixed a sampling rate of 2.56 MHZ. This device is beneficial in detecting a signal and analyzing its spectrum. [24], [25].

Technical characteristics:

- Frequency range: 25 MHz – 1750 MHz.
- Sample rate: from 250 KHz up to 3:2 MHz.
- Modulation techniques: FM, FMS, NBFM, AM,
- LSB, USB, DSB & I/Q.
- Audio sample rate: 44:1 KHz to 96 KHz

Spectrum Analyser Tektronix MDO4054-3

It is an oscilloscope with an implicit range analyzer from Tektronix. It is capable of catching time-associated (Figure 3.5): Experimental set-up of the testbed prototype. Simple, advanced, and RF signals [26]. In our prototype, we are using this hardware as an additional spectrum analyzer.

Spectrum Analyser Technical characteristics

- Frequency Range: 50 KHz – 3 GHz
- Bandwidth: 500 MHz, span 1 KHz – 3 GHz

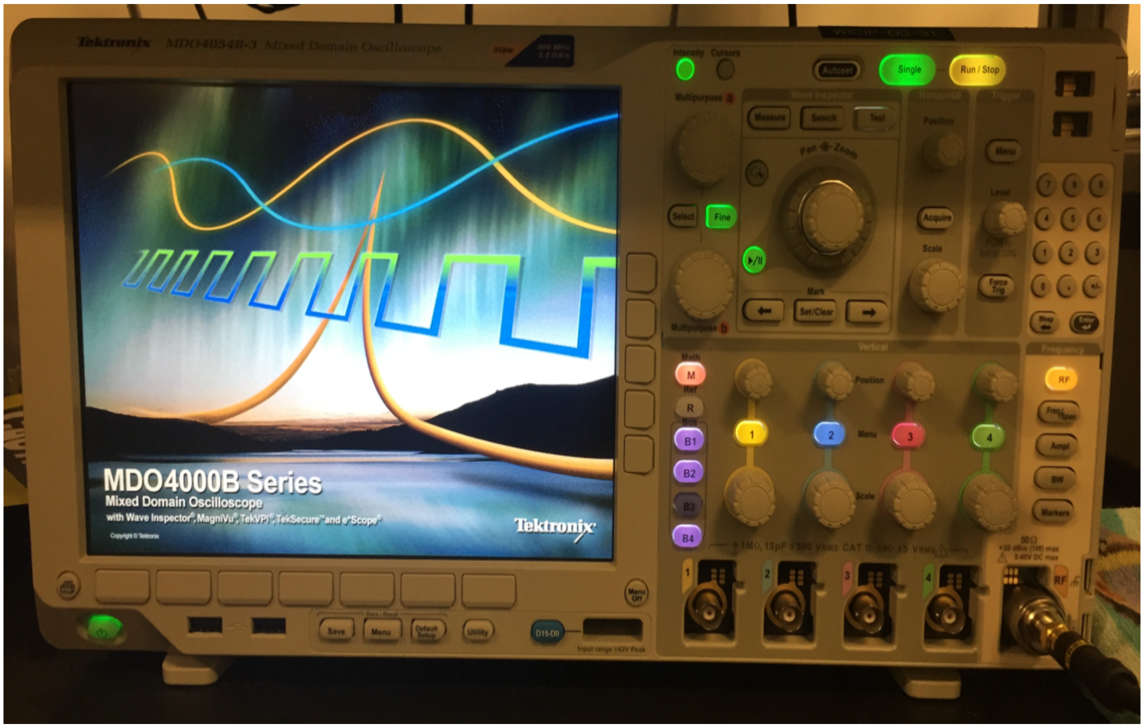


Figure 3.5 Spectrum Analyser Tektronix MDO4054-3.

- Frequency Resolution: 20 Hz – 10 MHz
- Average Noise Level: 115dBm
- Amplitude Resolution: 0:5dBm
- Automatic RBW: 2:6 KHz-600 KHz

3.4 SDR Platform and Basics

SDR is a definitive radio innovation, joining two key advancements: digital radio, and PC programming. With advanced radios, the majority of the signal preparing is made in the computerized area, keeping it as close as conceivable to RF front-end, and the single segment of the radio to the fundamental (up conversion and intensification). Parts that have been regularly actualized in equipment (e.g., mixers, filters, intensifiers, modulators/demodulators, detectors, and so on.) are achieved by methods for programming or programmable hardware. Simply put Software Defined Radio is defined as [27]: "Radio in which some or all of the physical layer functions are software defined."

The conventional radio is expensive to adjust radio hardware, yet SDR (programming characterized radio) innovation brings a parcel of adaptability and costs effectiveness since it is a product based way to deal with accomplishing variable correspondence programmable necessities. Programming Defined Radio [28] presents software pieces rather than equipment parts to get motions all together concentrate data.

Programming characterized radio's works by modifiable programming or firmware working on programmable handling innovations, for example, Field-Programmable Gate Array (FPGA), Digital Signal Processing (DSP), General Purpose Processors (GPP), System on Chip (SOC), and other explicit application programmable processors. The accommodation picked up by utilizing these advancements is that it is anything but awkward to include new abilities and remote highlights to existing radio frameworks by programming without changing required new equipment cost. The fundamental diagram and essential elements of SDR can be illustrated in Figure 3.6.

To begin with, the analog to digital converter (ADC) and the digital to analog (DAC) resemble the scaffolds between the consistent, simple signs from the physical world and discrete computerized tests controlled by programming.

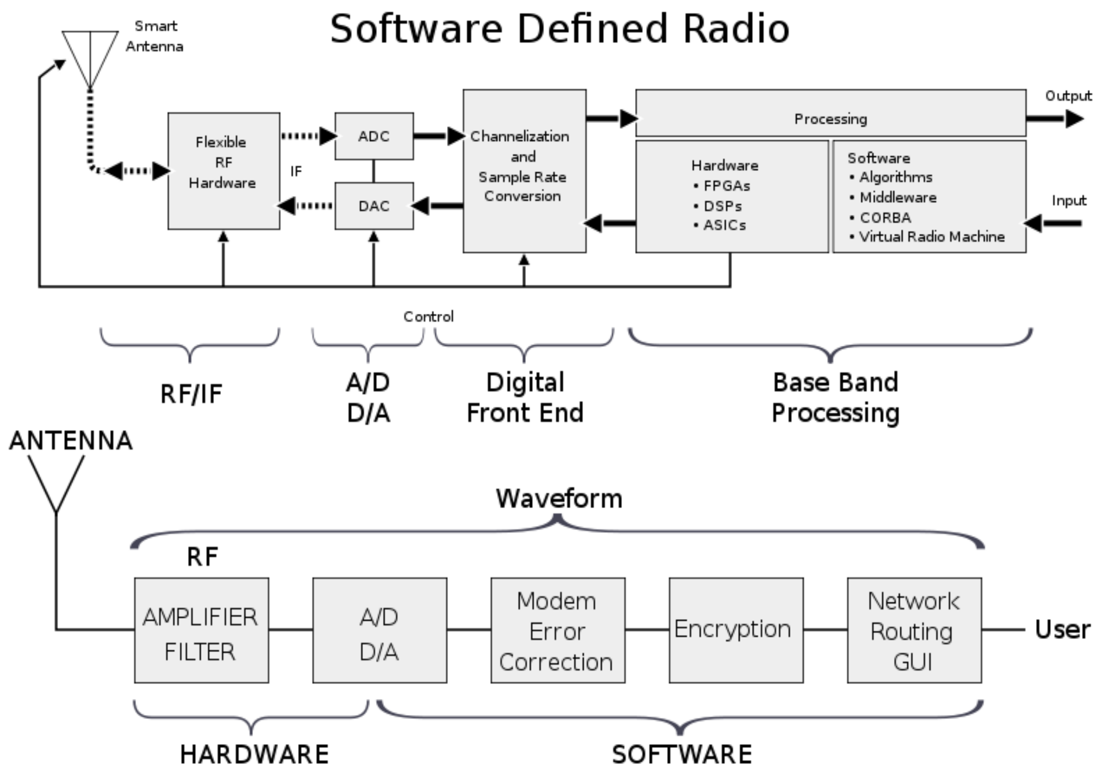


Figure 3.6 Basic architecture of a SDR. Source: [29].

For the ADC, it has two essential attributes: inspecting rate that is the times each second of the simple flag estimated by ADC; dynamic range that is the distinction between the littlest and biggest flag that can be recognized, it's an element of the number of bits in the ADC's advanced yield and the plan of the converter.

From Nyquist examining hypothesis, we realize that the ADC sampling frequency must be somewhere around double the most bandwidth frequency of the signal with the goal that the associating can be maintained a strategic distance from. So, there is an issue, if the ADC keeps running at 30 MHz, we can't tune in to communicate FM radio at 99.1 MHz, in any case; with the RF front-end, we can interpret signals happening in 90-100 MHz go (RF) down to 0-10 MHz extend (IF), at that point tuning in to the radio at 99.1 MHz with

20MHz ADC testing rate is conceivable. Because SDR is a convenient and inexpensive tool for communication system development, there are a great many groups and companies are working on it. Finding SDR hardware and toolkit in the market is straightforward. Table 3.1 shows some available SDR hardware and software resources [30].

Table 3.1 SDR hardware and software resources

Producer & Website	Name	Frequency Range	Sampling Rate	Products Based Price
USRP Ettus Research LLC http://www.ettus.co m/products	USRP B200	70 MHz – 6 GHz	56 Msps	US$675
	USRP B210	70 MHz – 6 GHz	56 Msps	US$1,100
	USRP N200	DC – 6 GHz	25 Msps for 16-bit samples; 50 Msps for 8-bit samples	US$1,515
	USRP X300	DC – 6 GHz	200 Msps	US$3,900
	USRP X310	DC – 6 GHz	200 Msps	US$4,800
Rice University WARP http://mangocomm. com/products	WARPv3	2.4 GHz and 5.8 GHz	40 Msps	US$6,900
FlexRadio FlexRadio System http://www.flexradio.com	FLEX-6700	0.01 – 73, 135 – 165 MHz	245.76 MSPS	US$7,499
	FLEX-6500	0.01 – 73 MHz	245.76 MSPS	US$4,299
Producer & Website	Name		Sampling Rate	

		Frequency Range		Products Based Price
	FLEX-6300	0.01 – 54 MHz	122.88 MSPS	US$2,499
	FLEX-3000	0.01 – 65 MHz	48, 96 kHz	US$1,700
	FLEX-1500	0.01 – 54 MHz		US$650
SDR-IQ RFSPACE.Inc http://www.rfspace.com/RFSPACE/SD R-IQ.html	SDR-IQ	0.1 kHz – 30 MHz	66.666 MHz	US$525
DRM Supporter http://www.nti-online.de/edirabox.h tm	DRB30	30kHz-30MHz	External ADC required (I/Q output)	US$390
QS1R	QS1R	10 kHz – 62.5 MHz (up to 500 MHz using images/alias)	130 MHz	US$900

3.5 GNU Radio

GNU Radio is an open source software. It has encoding and decoding signal processing package kit tool kit. To run the software defined radio, GNU Radio provides the signal processing run time and processing blocks to implement software defined radio [31]. GNU Radio allows programmers to execute SDR applications on all kinds of PC operating systems, like Linux, Windows, UNIX and Mac OS. In this research, Ubuntu Linux operating system was used. To aid beginners, Josh Blum of Johns Hopkins University, has developed a graphical interface for GNU Radio. This GUI termed GNU Radio Companion (GRC), allows users to interact with GNU Radio signal blocks like LabView or Simulink. The entire interface is entirely designed with GNU Radio in mind, and encompasses over 150 blocks from the GNU Radio Project. GNU Radio offers various building blocks for signal processing, as well as a method to manipulate the data flow between the blocks. This is a partial list of the functions offered by GNU Radio software platform including:

- Mathematical operations such as add, subtract, multiply, divide, power, logarithm and logic operations;
- FFT/IFFT blocks
- Filters including High pass filter, low pass filter, band pass filter, band reject filter, FFT filter, Finite Impulse Response (FIR) filter, Infinite Impulse Response (IIR) filter and Hilbert;
- Modulations and demodulations such as FM, AM. PSK, QAM, Differential Encoder, Differential Decoder and OFDM;
- Control blocks including Automatic Gain Control (AGC) blocks, Detect Peak block, Threshold block;
- Type conversions such as Float to Short block, Int to Fload block, and Complex to Real
- Line coding such as Scrambler, Descrambler and Adaptive Scrambler
- Channel coding such as Trellis coding and Viterbi decoding.

GNU Radio software platform also offer support for different signal sources and sinks as following:

- Constant source;
- Noise source;
- Pseudo random number source;
- Random vector source;
- USRP source and sink;
- Message source;
- Graphical sinks such as Oscilloscope sink, Eye Diagram, FFT sink, Waterfall sink, Constellation sink and Histogram sink;
- Audio source and sink;
- File source and sink;
- Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) source and sink.

GNU Architecture

GNU Radio software architecture includes two components. The first one is the set of various C++ blocks which implement digital signal processing operations for example filtering, I/O operations, FFT/IFT, coding/decoding, and modulation/demodulation. The second one is the framework implemented as Python scripts to control the data flow among blocks. The use of Python scripts (Figure: 3.7) allows easy reconfiguration and manipulation of various functionalities and parameters of the system. Similar to connecting physical RF building blocks to construct a hardware radio, any user can build an SDR system by "wiring" together building blocks. USRP boards are general purpose RF hardware for GNU Radio architectures [32]. The main task of USRP boards is performing computationally intensive operations such as filtering, up-conversion, and down-conversion. The USRP, USRP2 and its current version USRP N-series are connected to a computer via a USB 2.0 and an Ethernet cable, respectively, and the GNU Radio software platform provides a robust Application Programming Interface (API) to control the USRP device. In GNU Radio all blocks are written in Python programming language; however, signal processing blocks are implemented in C++. GNU Radio takes this advantage and combines C++ and Python to construct applications to make it optimized signal processing code and also the user-friendly.

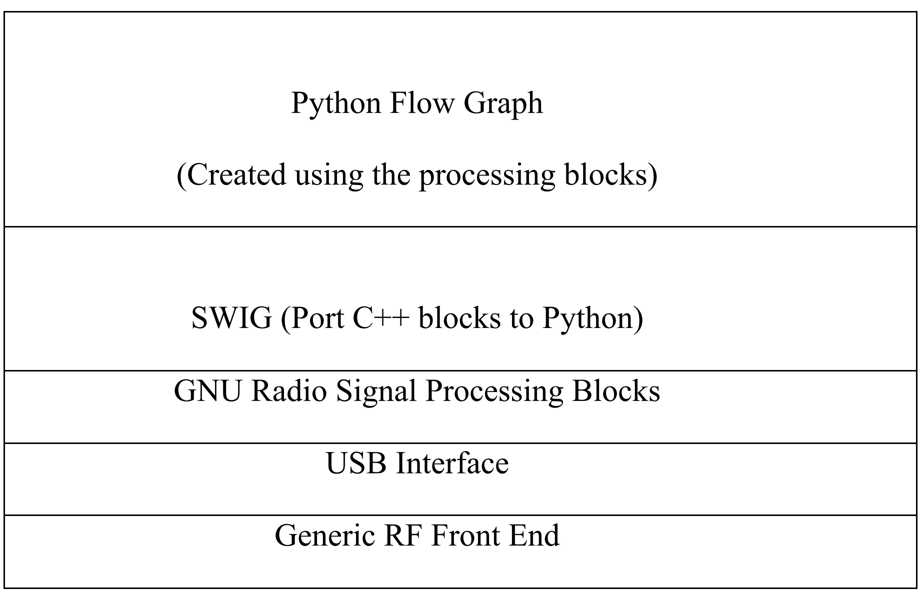


Figure 3.7 GNU Radio block diagram.

Simplified Wrapper and Interface Generator (SWIG) which comes between Python and C++ is used as the glue between them. The users can design their blocks using C++ and install those blocks to the library after generating the Python code by SWIG. Graphs are constructed and run in Python.

3.6 USRP Features

The Universal Software Radio Peripheral is the most widely recognized equipment utilized with GNU Radio to construct an SDR framework. USRP is a group of equipment gadgets found by Matt Ettus which encourage making SDRs. The daughterboard can without much of a stretch be traded. This permits USRP to work at different frequencies A typical setup of the USRP board consists of one motherboard and up to four daughter boards. In this prototype, a National Instrument (NI) USRP-2901 has been used to transmit the signal, and it has ports for two receiver antennas [33], as well as, two

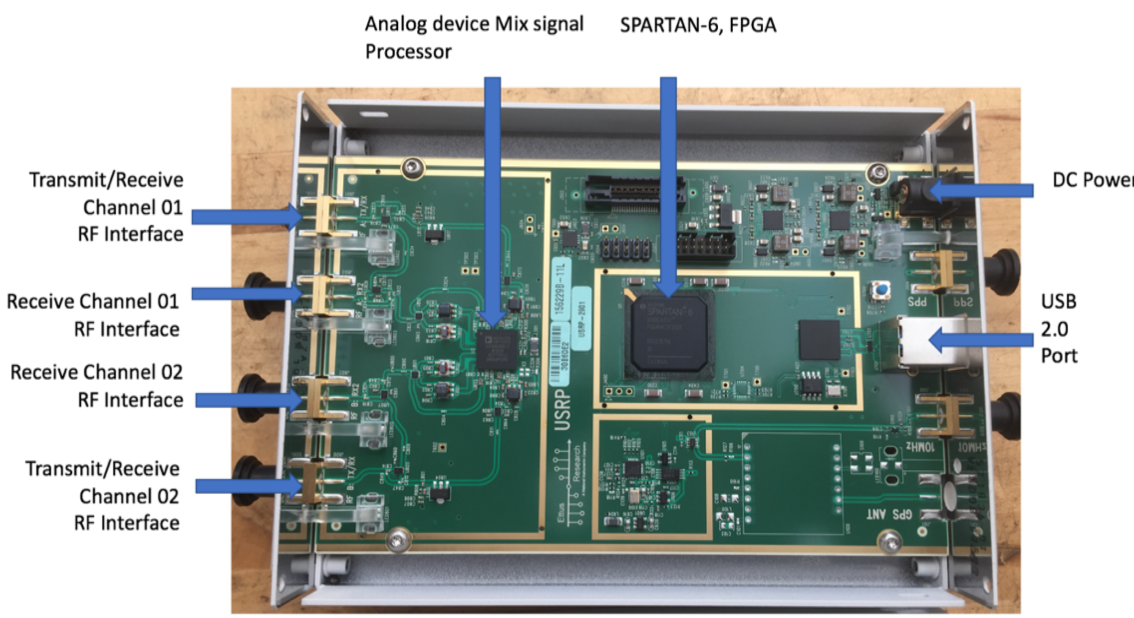


Figure 3.8 USRP 2901

transmitter antennas. The entire schematics design of the USRP is open source as shown In Figure 3.8. The USRP SDR Device is a tunable universal software radio peripheral transceiver for prototyping wireless communication systems. The USRP2901 specification [34] given below:

Table 3.2: USRP 2901 Specifications

Technical characteristics	Transmitter	Receiver
Frequency Range	70MHz to 6GHz	70MHz to 6GHz
Frequency step	<1KHz	<1KHz
Max. output power (Pout)	20dBm	N/A
Gain range	89.75dB	76dB
Gain step	0.25dB	1.0dB
Digital-to-analog converter	12 bits	N/A
Analog-to-Digital converter	12 bits	N/A
Max. instant. real-time BW	56 MHz	N/A
Max. input power (Pin)	N/A	−15dBm

The motherboard is made out of an onboard available Field Programmable Gate Array (FPGA) and an installed/removable memory. At the first run through utilizing the USRP gadget, USRP firmware and FPGA picture must be downloaded into the memory. At that point, the device can compare with any PC introduced USRP Hardware Driver (UHD), through a Gigabit Ethernet (or USB port in USRP USB arrangement). Aside starting from the digital change, talked about later in this segment, the FPGA does not play out any progressed computerized flag handling, for example, adjustment, modulation/

demodulation, and coding. Such preparing is continuously done in the PC. The fundamental objective of USRP motherboards is to change over primary IF signs to cutting edge baseband signs and the different way. To change over analog signs to digital signs, the motherboard utilizes two fast, simple to-computerized converters. The digitalized IF signal is then executed in the onboard FPGA. In that, the digital destroying low pass channel preloaded in the FPGA forms the signal. For the most part, the information rate of this digitalized signal is unreasonably high for general PC preparing. In this manner, the motivation behind sifting is to lessen the examining rate to suit the handling abilities of the PC and the limit of the Ethernet link.

Along the transmit way, digital data is sent to the FPGA which is changed over to a simple flag with two rapid advanced to-simple converters. The pure signal is then bolstered to the daughterboard to transmit as an RF signal. It has two antennas named TX/RX and RX2 one on each interface. The TX/RX antennas can be used either for transmission or reception; however, RX2 antennas are only used for reception. Depending on the application of the SDR communication script User can select the preferred antennas. The interfaces available are:

- Transmit only: User must select TX/RX for transmission
- Receive only: Either TX/RX or RX2 can be selected. To receive two frequencies booth antennas cannot be used at the same.
- Full-duplex mode: In this mode, FPGA automatically selects TX/RX as the transmit path and RX2 as the receive path.

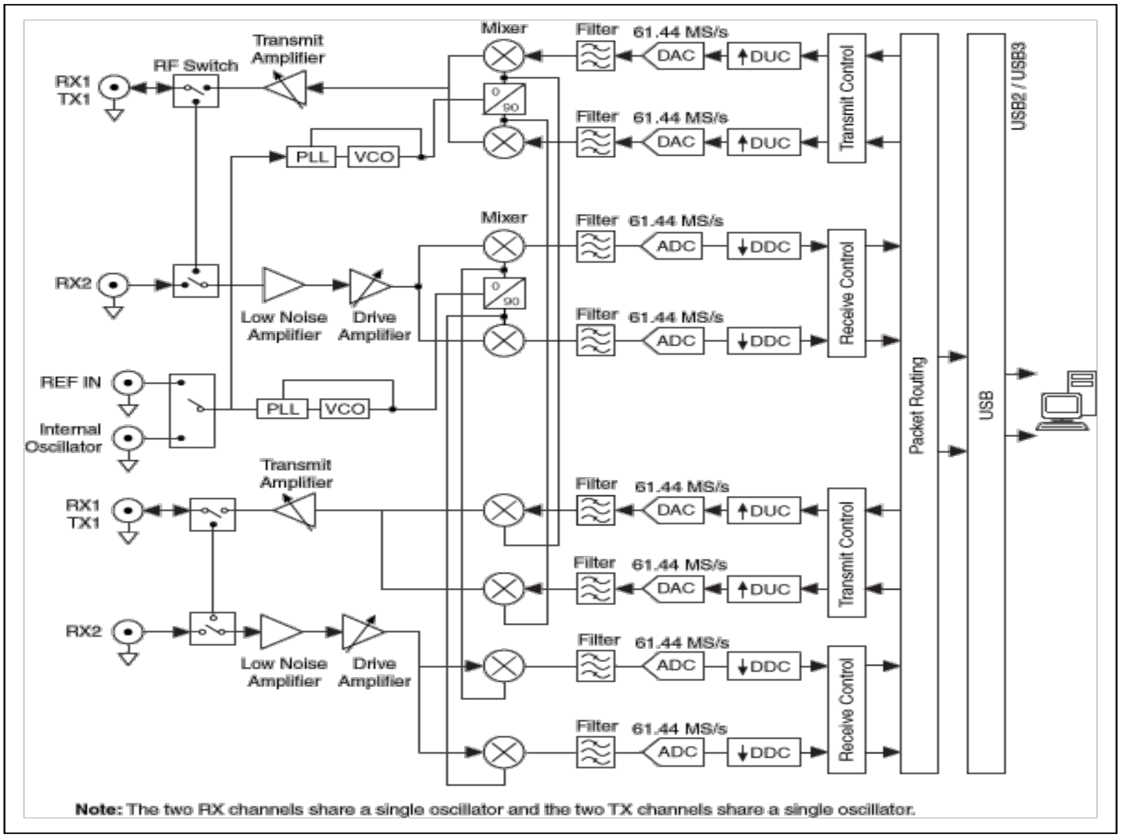


Figure 3.9 USRP-2901 Block Diagram Source: [36].

The RF switch allows transmit and receive operations to occur on the same shared antenna [35]. On the USRP-2901, one antenna is designated receive-only. The working principle of USRP 2901 Figure 3.9 is describing below:

Receive Path:

- The incoming signal is amplified by the low-noise amplifier and drive amplifier.
- The phase-locked loop (PLL) controls the voltage-controlled oscillator (VCO) so that the device clocks and local oscillator (LO) can be frequency-locked to a reference signal.

- The signals converted by the mixer down into in-phase (I) and quadrature-phase (Q) components.
- The noise and high frequency components in the signal is reduced by the bandpass filter.
- The analog-to-digital converter (ADC) digitizes the I and Q data.
- The digital downconverter (DDC) mixes, filters, and decimates the signal to a user-specified rate.
- The down converted samples are passed to the host computer over a USB 3.0 or USB 2.0 connection.

Transmit Path:

- The host computer synthesizes baseband I/Q signals and transmits the signals to the device over a USB 3.0 or USB 2.0 connection.
- The digital up converter (DUC) mixes, filters, and interpolates the signal to 61.44 MS/s.
- The digital-to-analog converter (DAC) converts the signal to analog.
- The bandpass filter reduces noise and high frequency components in the signal.
- The mixer up converts the signals to a user-specified RF frequency.
- The PLL controls the VCO so that the device clocks and LO can be frequency-locked to a reference signal.
- The transmit amplifier amplifies the signal and transmits the signal through the antenna.

3.7 Simulation

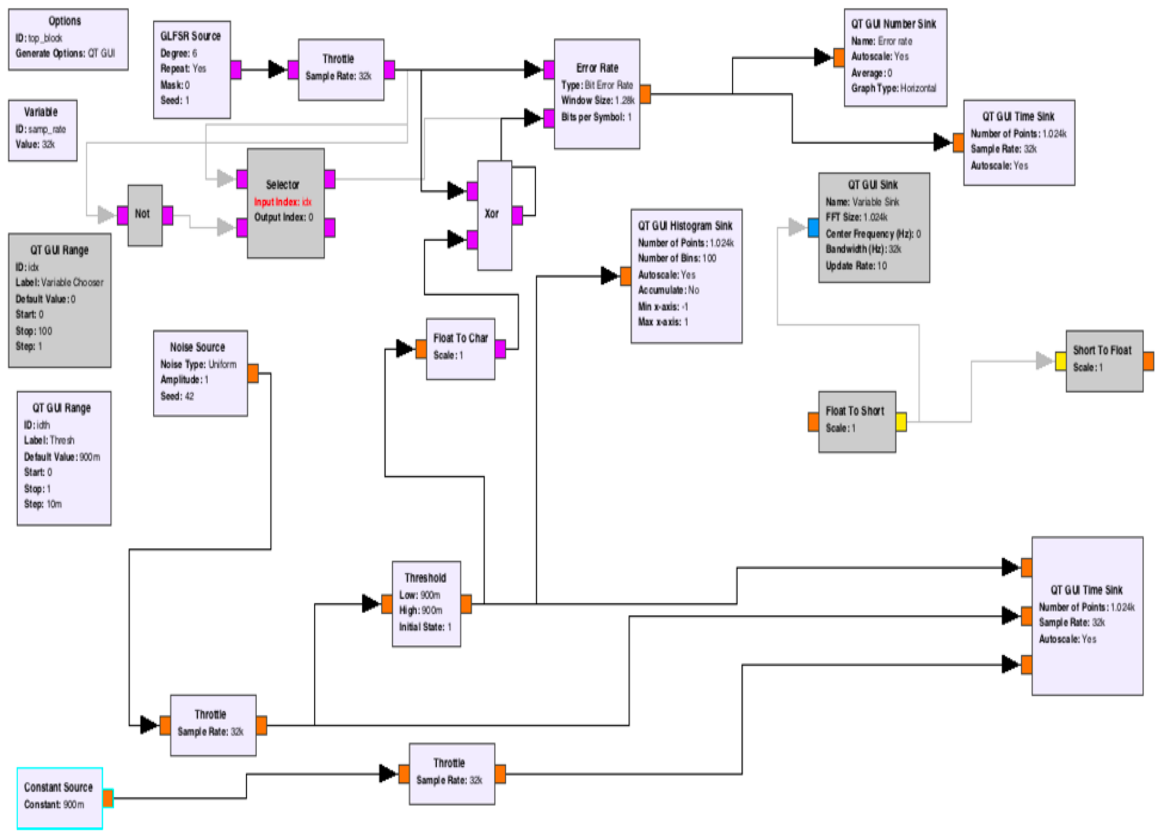


Figure 3.10 Simulation of Bit Error Analyse.

In this simulation, we have tried to using GRC Block and calculating the bit error rate. We have generated binary output using the random source, and passing through it to the XOR gate. There are one more input in the XOR gate is from the Noise source. If Two data are not matched than the output of XOR will flip about the Signal source. We can calculate the bit error rate by Error Rate block in Gnu Radio. The GRC block diagram shown in Figure 3.10.

•**GLESR:** This source block produce bytes stream.

•**Error rate block:** Compare the data coming in input port with original data in reference.

•**Xor Block:** it controls those bits will be corrupted or flip. If it is zero (0) then data will be unchanged, otherwise (1) it will flip the output.

•**Noise Source:** The amplitude is 1 that will uniformly distribute between positive and negative one.

•**Threshold block:** Going to operate as a binary threshold, over the threshold value it produces one, under the value it gives zero.

•Visualize the output with: Number Sink, Time Sink and Histogram Sink block

Results: If threshold value is reducing from 950m then the noise block produce more one (1) bits and that means more flip bits and more original data corrupted. It would make bit error rate high 0.02 to 0.5 as shown in the Figure 3.11.

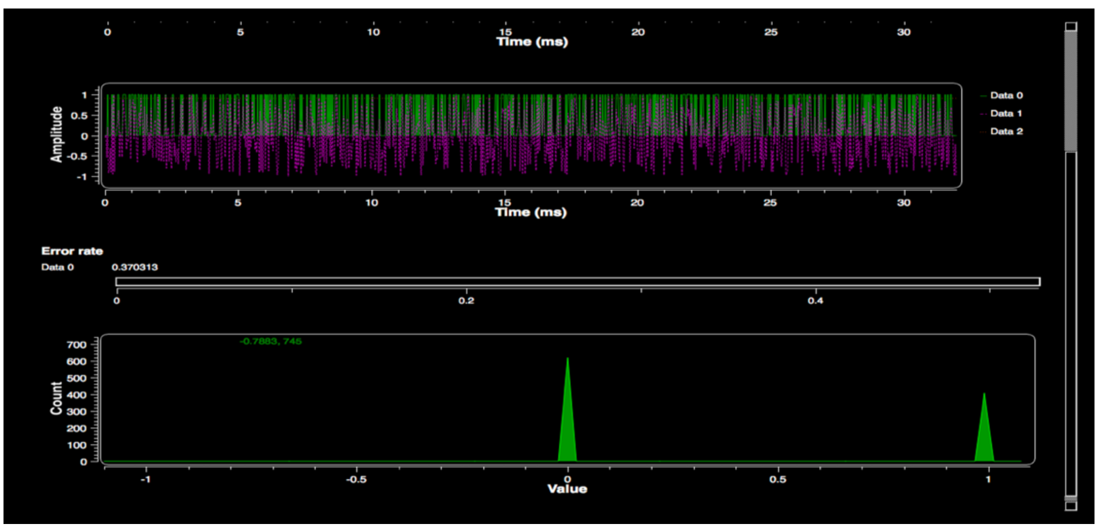


Figure 3.11 BER test (GLFSR source, biased random bit flips).

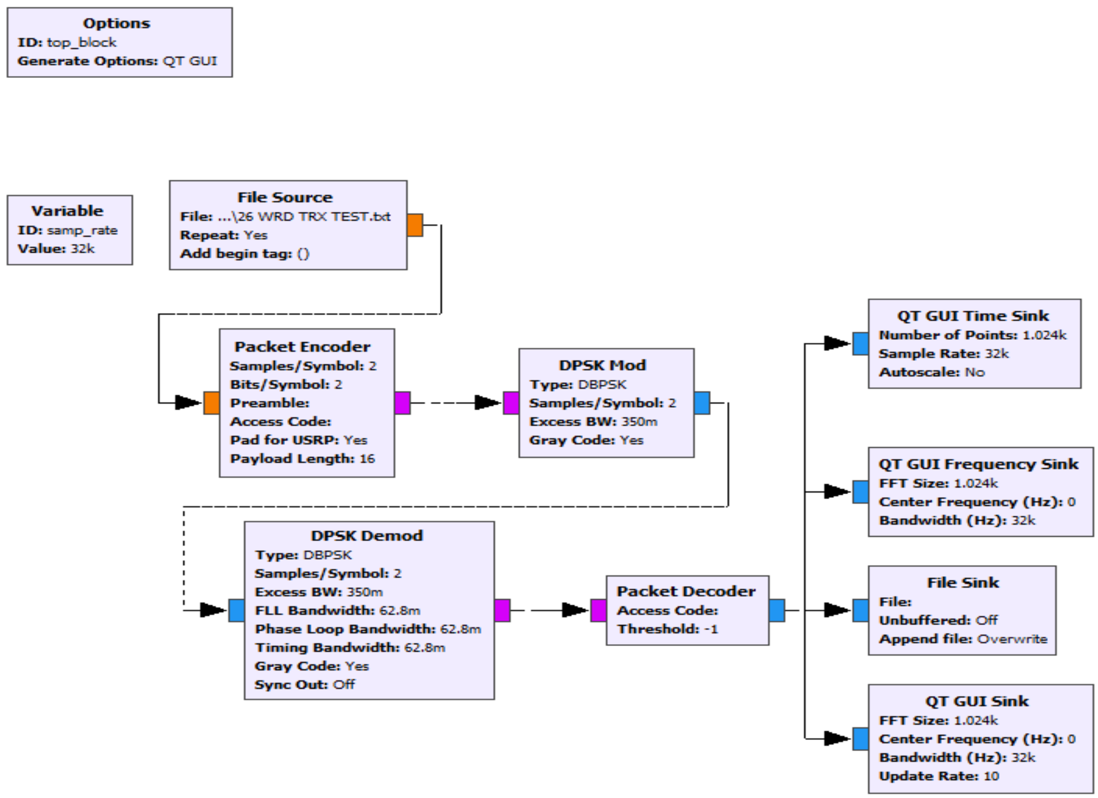


Figure 3.12 DPSK modulation GRC Block diagram for simulation.

A simple DPSK modulation [37] scheme is showing in Figure 3.12. We have done this simulation using GNU Radio. We have used this GRC block diagram to sending the text and imagine file before using the real-time transmission. This simulation was very useful to identify the parameters for example samples/symbol, bits/symbol, and payload length.

3.8 Conclusion: In this chapter, we have discussed our prototype and underlying theory of the relevant devices. Our focus is to use spectrum allocation more efficiently. So we have tried TVWS divided into sub-channels for more users. We have designed the prototype in this way so that it is possible to transmit and evaluate the communication scheme. We have done a simulation to understand how the GNU Radio works, and we have abled to observe the graphical presentation of FFT in QT sink.

CHAPTER IV

IMPLEMENTATION AND PERFORMANCE ANALYSIS

4.1 System Setup

The testbed was set up in the Wireless Communications and Information Processing (WiCIP) research laboratory situated in the Centre for Innovation and Engineering (CEI) building, The University of Windsor. Windsor, Ontario. Figure 4.1 shows the testbed set-up. The transmitter and receiver USRP devices were in a separation of 4 feet. Multiple transmissions were carried out to validate experimental results. Before we are going into the set-up and results, we at first mention the terrestrial TV channels in the Windsor region.

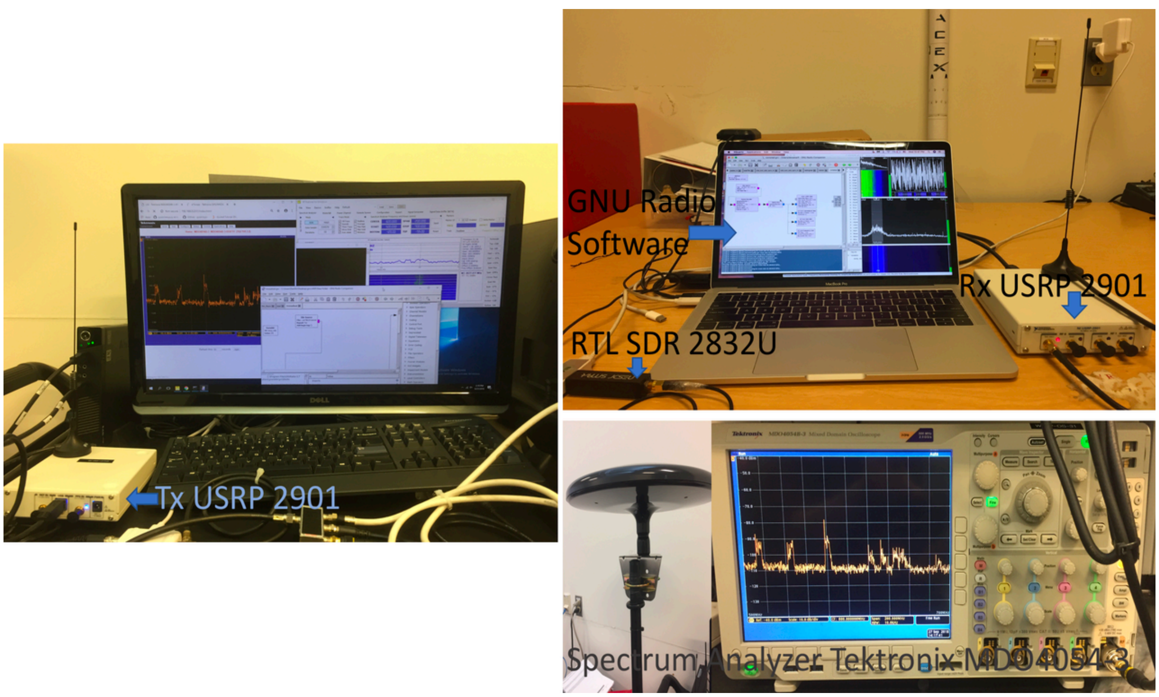


Figure 4.1 Experimental set-up of the testbed prototype.

4.2 Windsor TV Channel Occupancy

In Windsor, the bands IV and V, accommodate 33 UHF terrestrial TV channels and they occupy the frequency band 500MHz-698MHz, where each channel has a bandwidth of 6MHz [16]. In one of our prior works, by spectrum sensing, channels 22, 23, 24, 33, 36, 47, 48, 49 and 51 were identified as idle, channel 37 is allocated to radio space science, and the remaining 23 channels were found to be active. i.e., they had active Primary User (PU) [38]. We chose channel#23, occupying the spectrum of 524MHz-530 MHz as our transmission channel Figure 4.2.

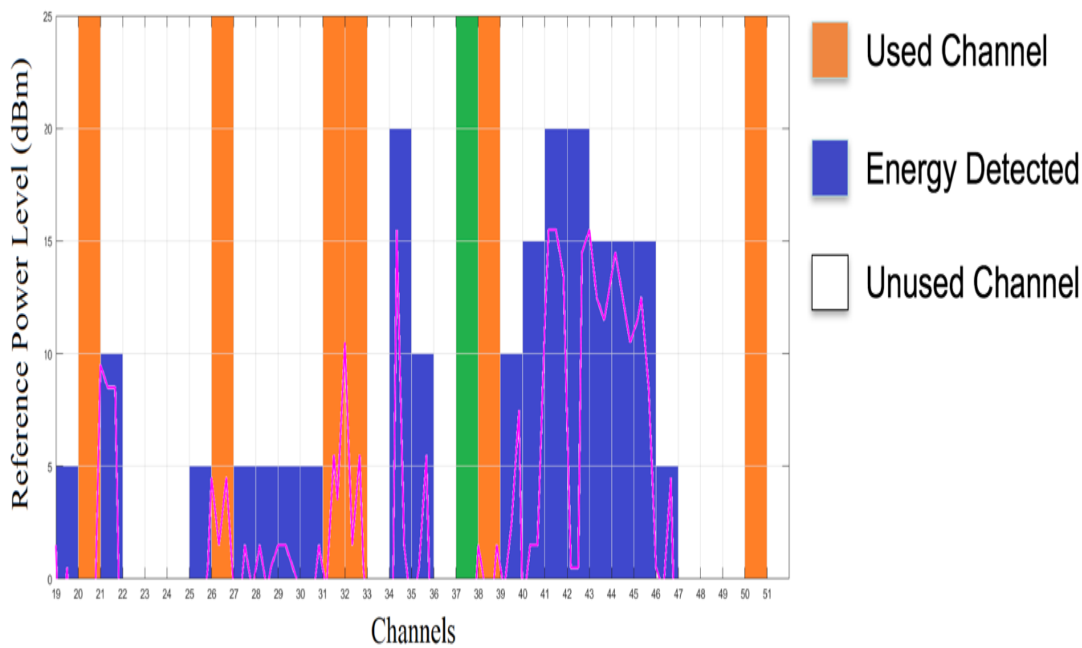


Figure 4.2 From 32 UHF TV channels, in orange are six active channels, in blue are 17 channels with energy detected by the MSSP, and nine white channels considered as TVWS.

All the terrestrial TV bands, corresponding channel number and bandwidths are listed below.

Band I: 54 - 72 MHz, channels 2 to 4.

Band I (Cont.): 76 - 88 MHz, channels 5 and 6.

Band III: 174 - 216 MHz, channels 7 to 13.

Band IV: 500 - 644 MHz, channels 19 to 42.

Band V: 644 - 698 MHz, channels 43 to 51.

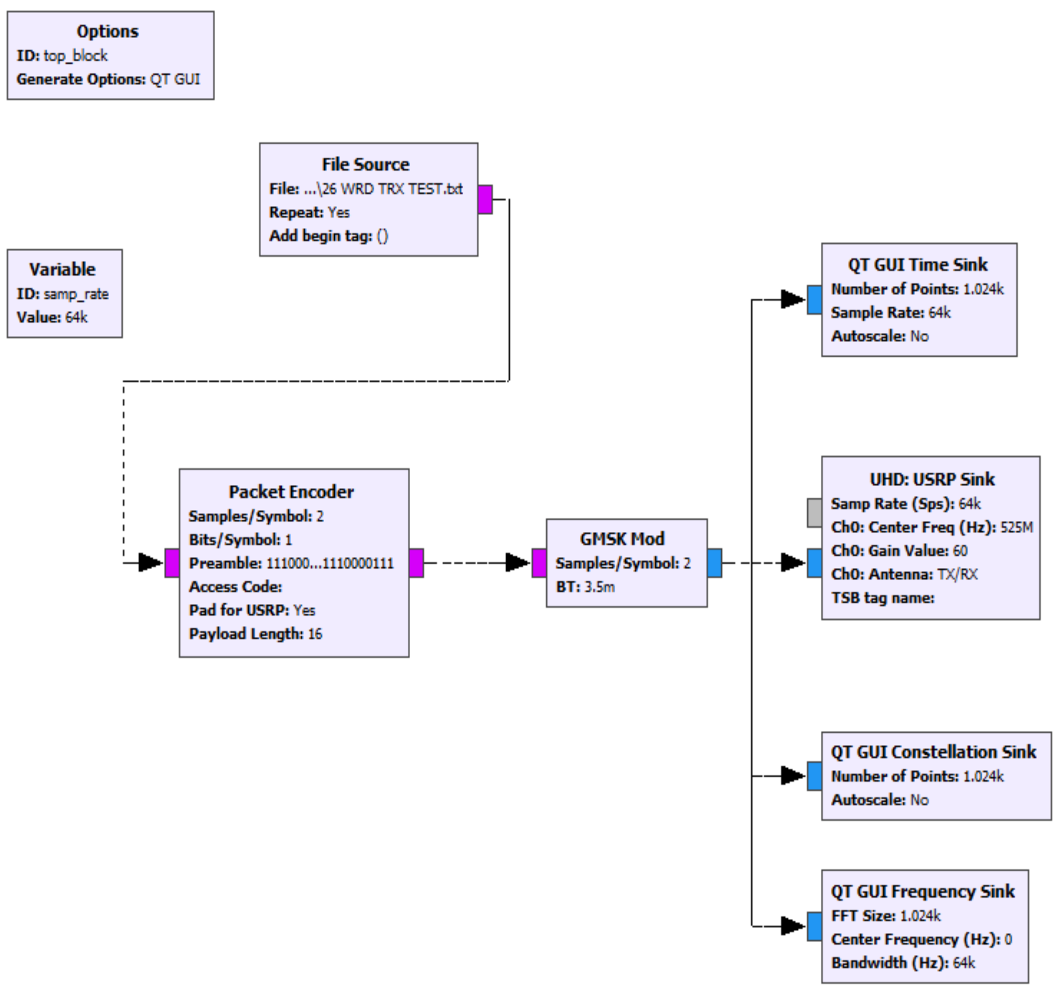
4.3 Transceiver Operation

In the transmission side, data from computer storage is fetched by GNU Radio as a binary stream. This stream is then converted into the small chunk of the equal number of bits forming packets. This packet data is then modulated to form IQ symbols that go into the USRP device [39]. On the USRP device, a local oscillator is used for carrier modulation, and the resultant modulated signal is transmitted through the antenna.

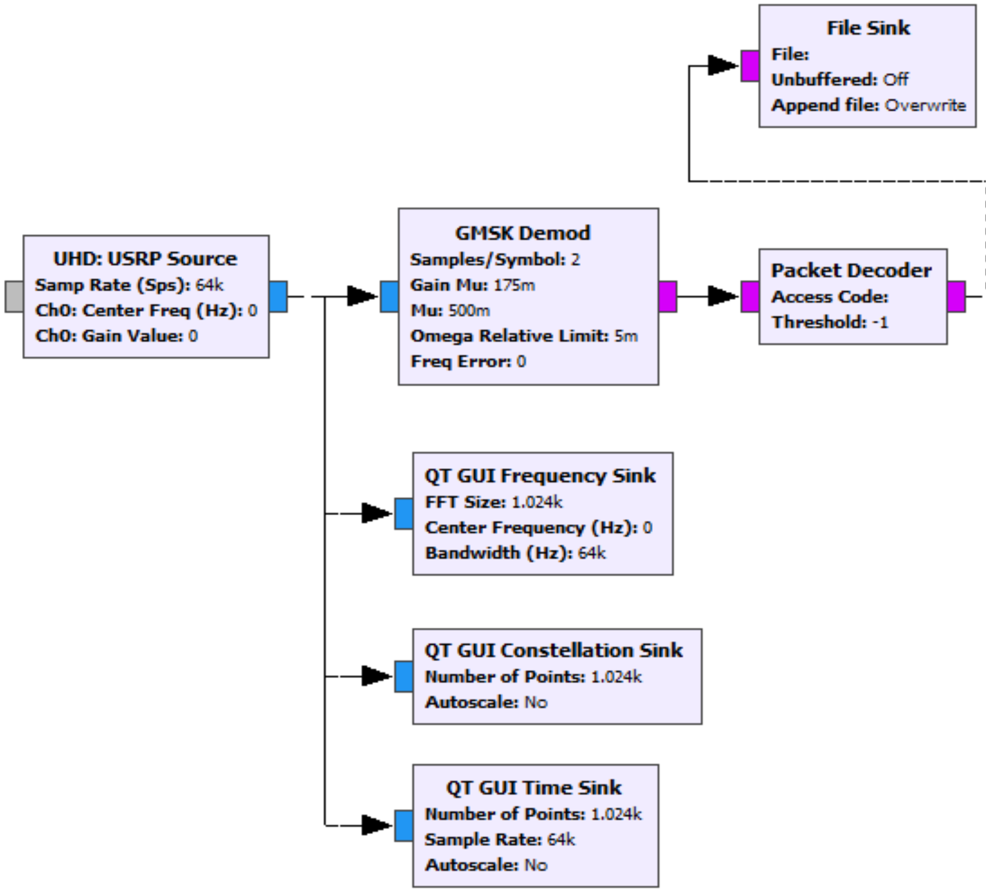
On the receiver side, the opposite operation of the transmitter takes place in USRP device and GNU Radio. Additionally, a spectrum analyser and RTL device are used for spectrum monitoring and analysing the received signal.

4.4 GRC Block Diagram

The functional blocks [40] used in GNU Radio are shown in Figure 4.3. The first block is the file source which reads raw data values in binary format. In the second stage, binary data passes through the packet encoder. The encoder forms packets based on the given payload and header. Every packet has the same access code and preamble. It is recommended adjusting the payload length, preamble and bits/symbol according to the size of the file. The next block is Gaussian Minimum Shift Keying (GMSK) modulation block. GMSK facilitates less bandwidth and power, regulation plan [40]. The fourth block of the transmitting scheme is the USRP sink which is an interface to the USRP Hardware Driver library for connecting, sending, and receiving data. The USRP sink contains parameters like device address, wire format, number of channels, antenna, bandwidth, sample rates, etc.



a) Transmitter side



b) Receiver side

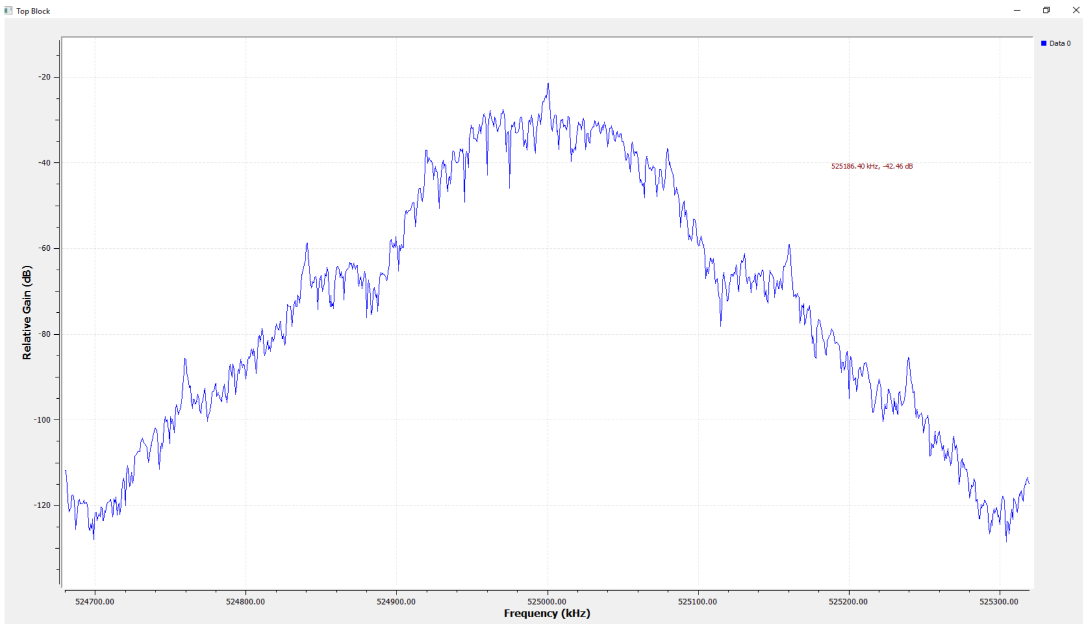
Figure 4.3 GRC functional blocks, transmitter side a) and b) receiver side.

The centre frequency is the overall frequency of the RF chain. Figure 4.4 (a) FFT of Real-Time Transmission at 525 MHz. The receiver side contains USRP source radio receiver samples and writes to a stream. The source block also provides API calls for receiver settings. The USRP will be able to en-queue several stream commands in the FPGA. What follows next are the GMSK Demodulation, Packet Decoder, and File Sink blocks.

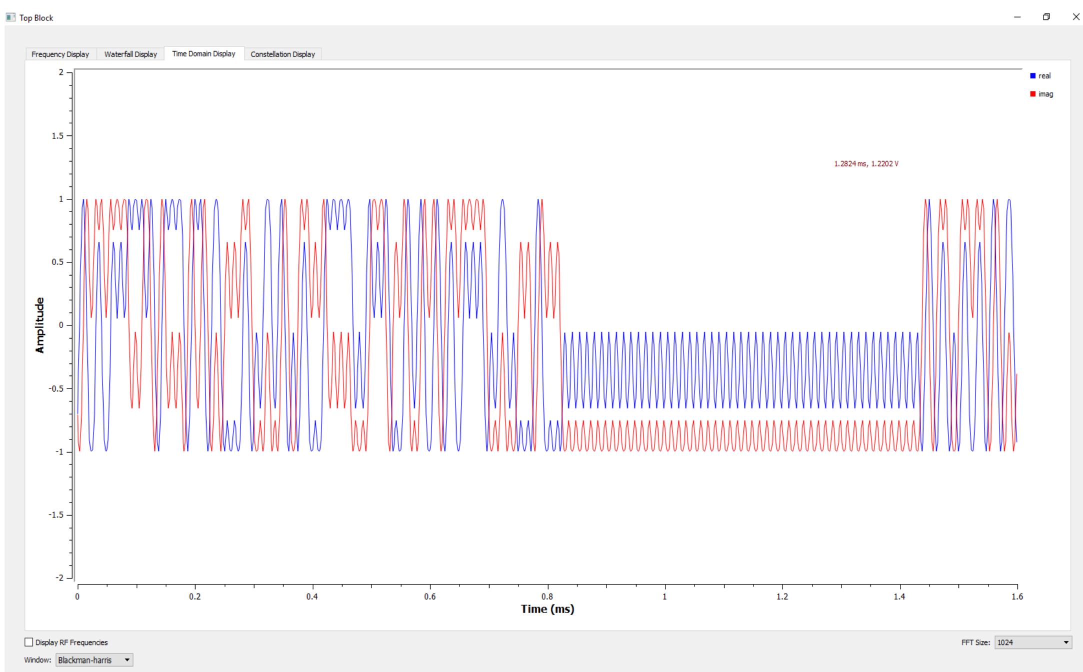
In Figure 4.4 (a) FFT a graphical display of multiple signals [42] in frequency. This is a QT-based graphical sink the takes set of a floating point streams and plots the Power Spectral Density (PSD). This plot is generated by applying a sampling frequency of 640k samples/sec to a 12-bit ADC with an analog input signal of 525 MHz. The signal at 525 MHz is the fundamental input signal. The signal describes the power present -30dB in the signal as a function of frequency.

Figure 4.4 (b) time domain represents a graphical sink to display multiple signals in time. This is a QT-based graphical sink the takes set of complex streams and plots them in the time domain. For each message, both the signal's in-phase (I) and quadrature (Q) parts are plotted, and they are all plotted with a different colour, and the and functions can be used to change the label and colour for a given input number. The IQ amplitude values (Y-axis) vary in between -1 to 1 and total time is 1.6ms.

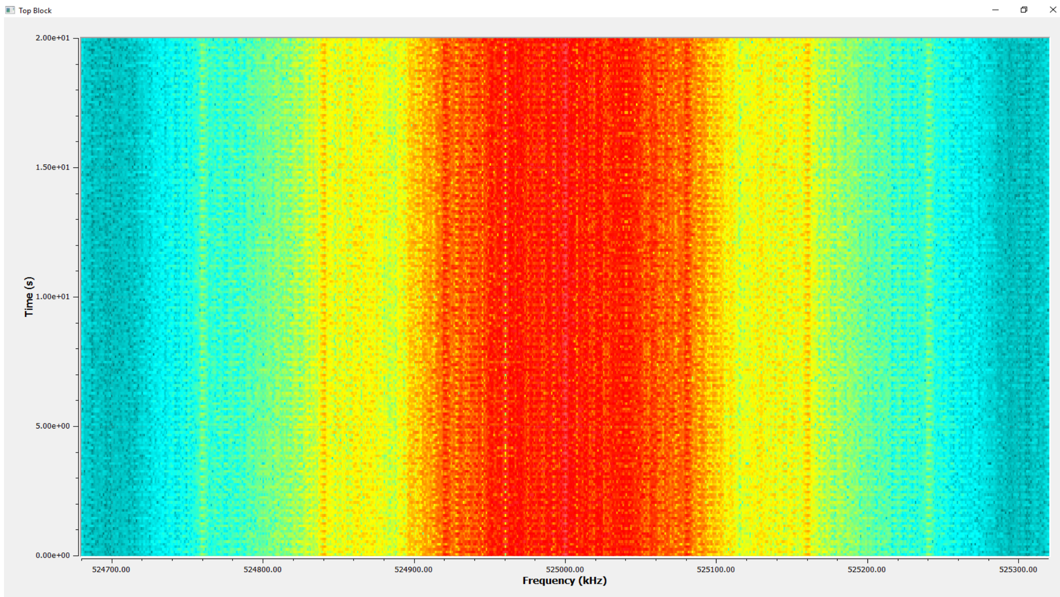
In Figure 4.4(c) waterfall A graphical sink to display multiple signals on a waterfall (spectrogram) plot. This is a QT-based graphical sink the takes set of a floating-point streams and schemes a waterfall (spectrogram) plot. The visual analyse of the spectrum of frequencies of a signal as it varies with time is done by the spectrogram. Waterfall plots are used to show the: results of spectral density estimation, illustrating the spectrum of the signal at successive intervals of time and delayed response produced by the impulse response. Frequencies are shown increasing up from 524.7 MHz to 525.7 MHz at the vertical axis, and time on the horizontal axis. The colour intensity increases with the spectral density.



a) FFT of Real-Time Transmission at 525 MHz.



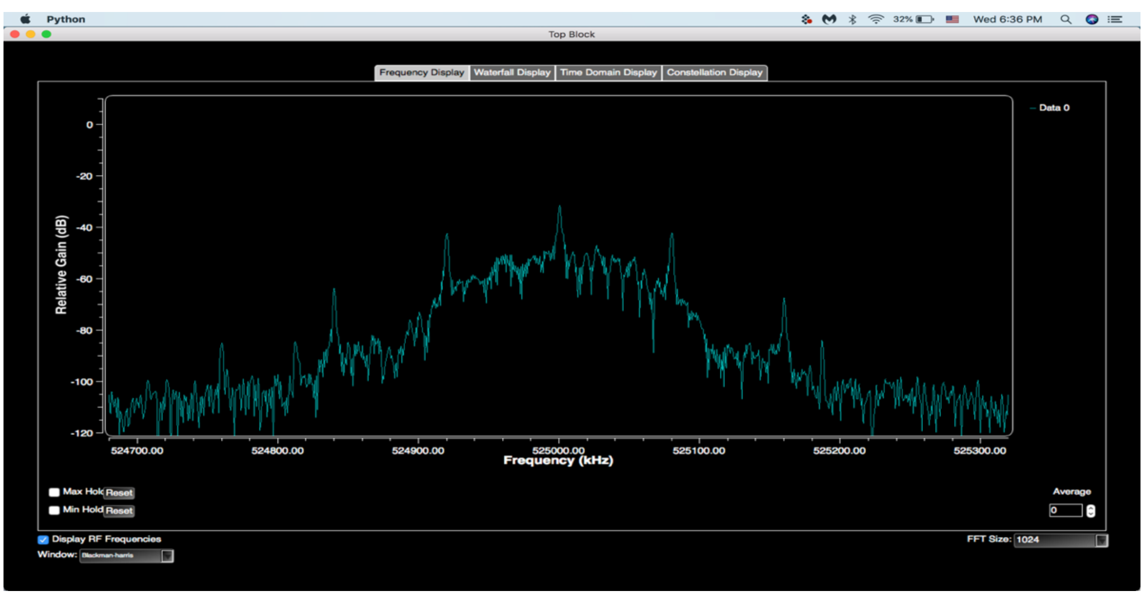
b) Time domain



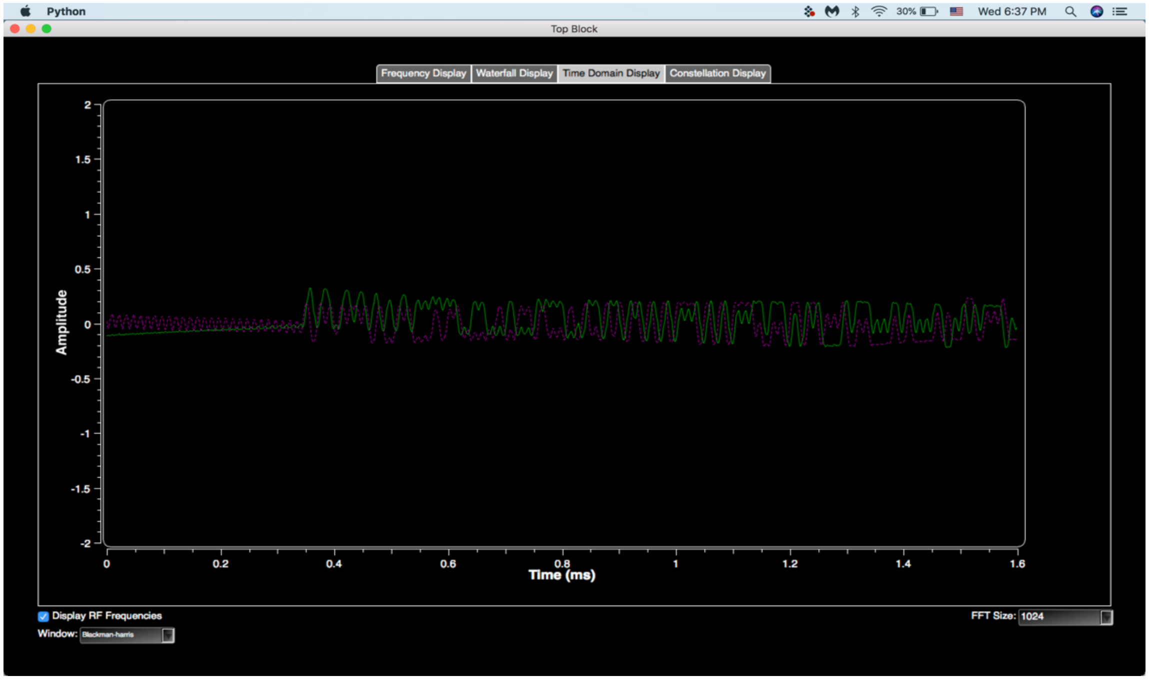
c) waterfall

Figure 4.4 Transmitter Part in Real-Time Transmission at 525 MHz a) FFT b) Time domain c) Waterfall

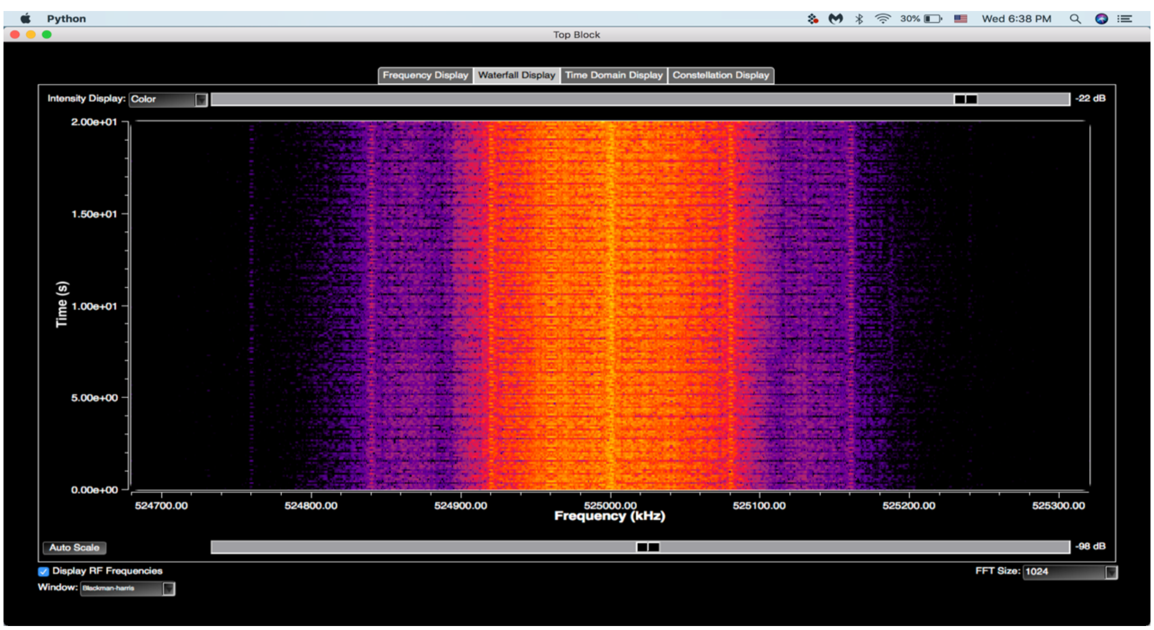
4.5 Performance Analysis



a) FFT



b) Time domain



c) Water Fall

Figure 4.5 In Receiver Side, Receiving Signal at 525MHz a) FFT, b) Time domain c) Waterfall

Table 4.1: SNR of the USRP and performance comparison

Tx EIRP	Rx Gain	Distance	Bandwidth	SNR
30 dB	40 dB	4 ft	200 kHz	0 dB
35 dB	40 dB	4 ft	200 kHz	5 dB
40 dB	40 dB	4 ft	200 kHz	10 dB
41 dB	40 dB	4 ft	200 kHz	11 dB
42 dB	40 dB	4 ft	200 kHz	12 dB
43 dB	40 dB	4 ft	200 kHz	13 dB
44 dB	40 dB	4 ft	200 kHz	14 dB
45 dB	40 dB	4 ft	200 kHz	15 dB
46 dB	40 dB	4 ft	200 kHz	16 dB
47 dB	40 dB	4 ft	200 kHz	17 dB
48 dB	40 dB	4 ft	200 kHz	18 dB
49 dB	40 dB	4 ft	200 kHz	19 dB
50 dB	40 dB	4 ft	200 kHz	20 dB
51 dB	40 dB	4 ft	200 kHz	21 dB
52 dB	40 dB	4 ft	200 kHz	22 dB
53 dB	40 dB	4 ft	200 kHz	23 dB
54 dB	40 dB	4 ft	200 kHz	24 dB
55 dB	40 dB	4 ft	200 kHz	25 dB
60 dB	40 dB	4 ft	200 kHz	35 dB
70dB	40dB	4 ft	200kHz	44dB
80 dB	40 dB	4 ft	200 kHz	55 dB

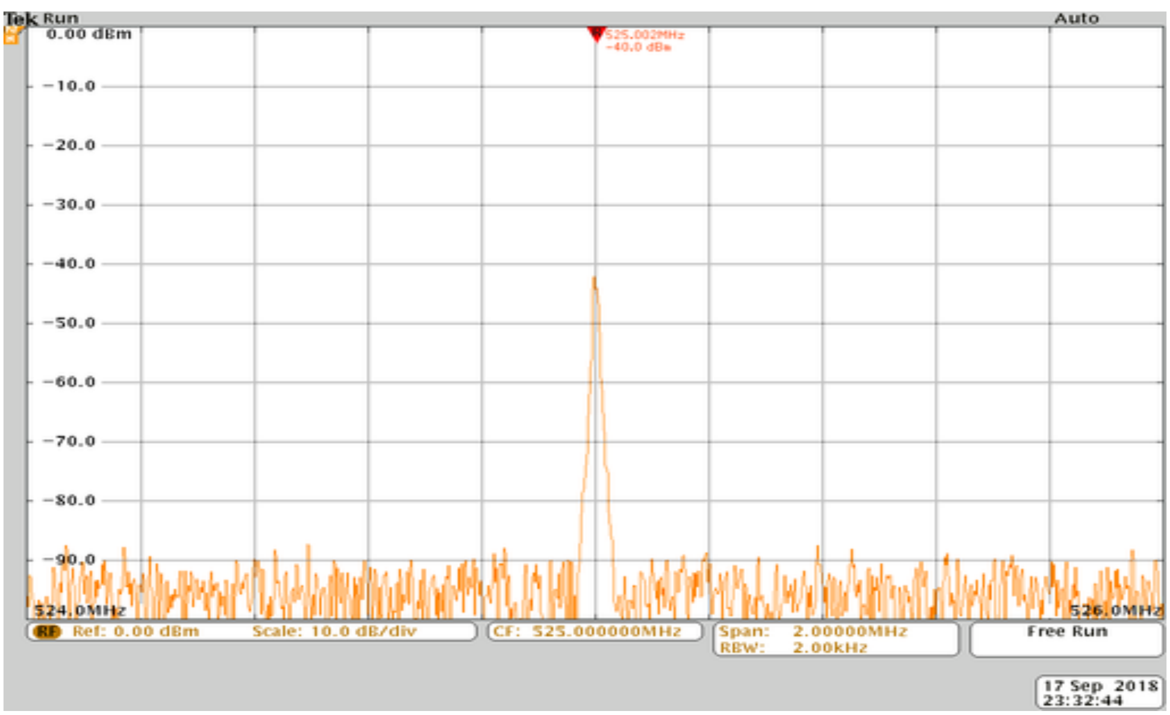
As mentioned before Channel#23 is the one that we are using in our work. Spanning over the spectrum of 524-530MHz, for this channel we chose the central frequency as

Table 4.2: USRP transmission power gain change vs Bytes.

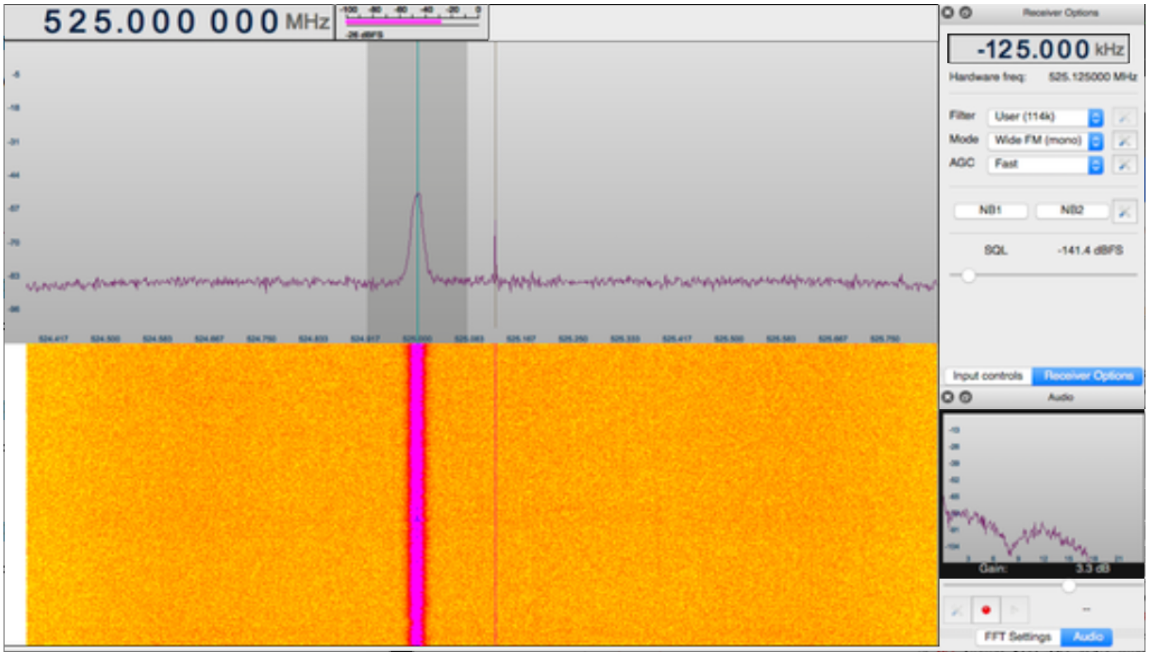
Tx EIRP	Rx Gain	Distance	Total Bytes	Received Bytes	Data Loss
30 dB	40 dB	4 ft	496 Bytes	0 Bytes	1
35 dB	40 dB	4 ft	496 Bytes	0 Bytes	1
40 dB	40 dB	4 ft	496 Bytes	16 Bytes	0.9677
41 dB	40 dB	4 ft	496 Bytes	32Bytes	0.9354
42 dB	40 dB	4 ft	496 Bytes	64Bytes	0.8709
43 dB	40 dB	4 ft	496 Bytes	128 Bytes	0.7419
44 dB	40 dB	4 ft	496 Bytes	176 Bytes	0.6451
45 dB	40 dB	4 ft	496 Bytes	272 Bytes	0.4516
46 dB	40 dB	4 ft	496 Bytes	352 Bytes	0.2903
47 dB	40 dB	4 ft	496 Bytes	400 Bytes	0.1935
48 dB	40 dB	4 ft	496 Bytes	416 Bytes	0.1612
49 dB	40 dB	4 ft	496 Bytes	420 Bytes	0.1532
50 dB	40 dB	4 ft	496 Bytes	432 Bytes	0.1290
51 dB	40 dB	4 ft	496 Bytes	464 Bytes	0.0645
52 dB	40 dB	4 ft	496 Bytes	480 Bytes	0.0323
53 dB	40 dB	4 ft	496 Bytes	496 Bytes	0
54 dB	40 dB	4 ft	496 Bytes	496 Bytes	0
55 dB	40 dB	4 ft	496 Bytes	496 Bytes	0
60 dB	40 dB	4 ft	496 Bytes	496 Bytes	0
70 dB	40 dB	4 ft	496 Bytes	496 Bytes	0
80 dB	40 dB	4 ft	496 Bytes	496 Bytes	0

525MHz and we exploited this channel by sending transmission file size of around 496 bytes. The FFT of 496 bytes of text file signal as shown in Figure 4.5 (a) FFT The X-axis represents the frequency which is 524.7MHz to 525.3MHz and the Y-axis is the Relative Gain (dB) which is -40 dB and the bandwidth of the signal is 200kHz.In Figure 4.5 (b) The IQ amplitude values (Y-axis) vary in between -0.5 to .5 and total time is 1.6ms. In Figure 4.5 (c) is represent the waterfall of the receiving signal, here the spectral density is than the transmitting signal. By changing the gain of the transmitter, we have calculated the Equivalent Isotropically Radiated Power (EIRP) as shown in Table 4.1 [43]. The received bytes are depicted in Table 4.2. The obtained result can be contrasted and verified by using Eqns. (1) and (2).

During the transmission, we have analysed the transmitted spectrum with the Spectrum Analyser Tektronix MDO4054-3 and RTL SDR 2832U, as is observed in Figures 4.7(a)



(a)



(b)

Figure 4.6 Secondary User on Channel 23, (a) Spectrum Analyser Tektronix MDO4054-3, (b) RTL Receive Signal.

and (b) Both graphs depict frequency vs. power. Form Tektronix Spectrum Analyser the power is -42dB whereas in the RTL the power is -50dB. In both cases, they represent the narrow bandwidth.

4.6 Results

In this experiment, GMSK modulation is used to transmit real-time data via GNU Radio and USRP. Selecting the payload length according to the file size is important. We have seen that Bit Transfer Rate (BTR) is varying proportionally with the transmitter power. We have changed the transmitter gain power from 15 dB to 80 dB, and we calculate the Bit transfer rate [44]. Results showed that BTR is improving according to the increase of the power of the transmitter, as is observed in Figure 4.8. At 15dB the BTR reaches 50% where is 22dB it reaches 100% of the BTR.

This result proves that when a TV channel is idle, it is possible to use it as an SU in the absence of the PU, and in this particular case, the possibility to allow the use of up to multiple narrowband users.

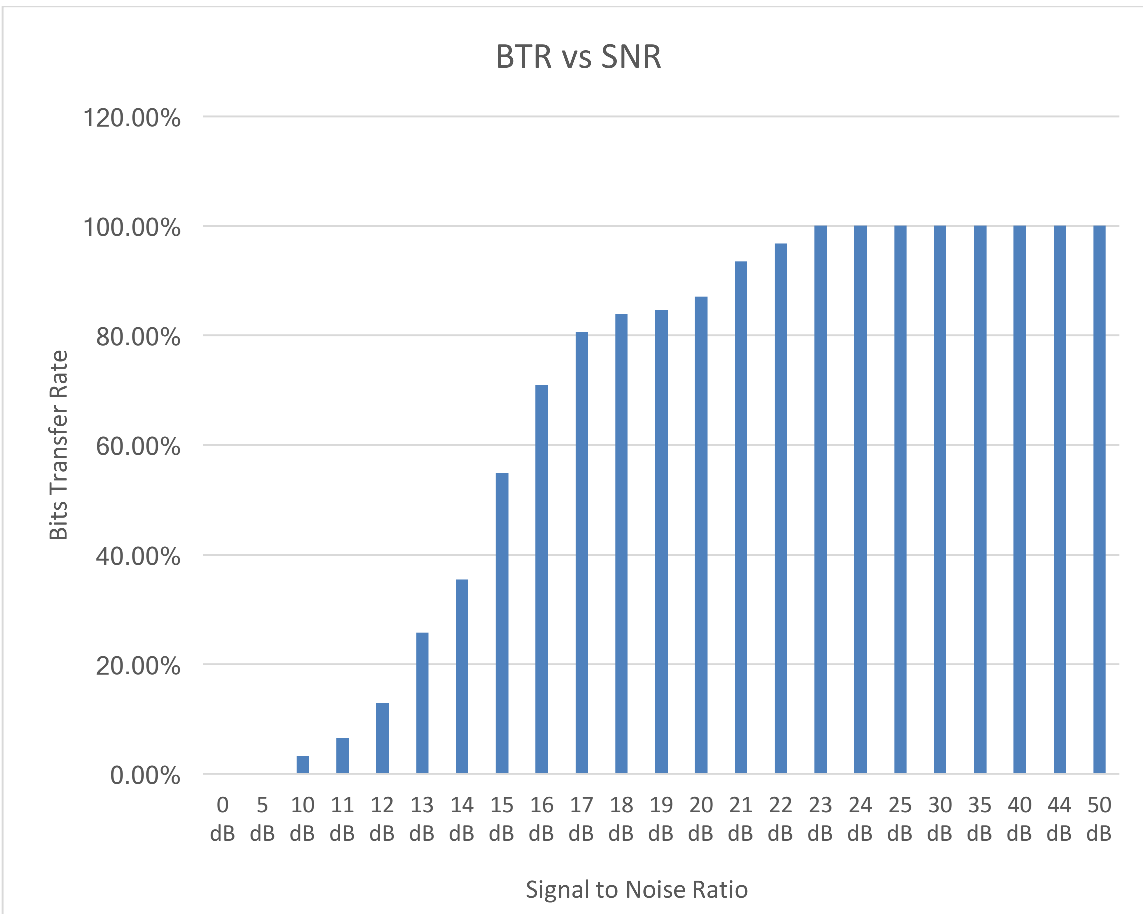


Figure 4.7 Bit Transfer Rate of using USRP 2901.

4.7 Chapter Summary

In this chapter, we have discussed the implementation of the prototype design. We show the TV channel occupancy in the Windsor region. From that, we know channel 23 is vacant, and there is no TV broadcasting. Therefore, we have transmitted a text file at particular frequency at 525 MHz. For that, we have prepared the GRC Block with GMSK modulation. We have also written a python code (Appendix A) to check the output of the each GRC Block in GNU Radio. There is MATLAB (Appendix A) code to check the bit error between original file and receive file. Running this code, we have found that there is no bit error with the BTR is 100% and SNR is more than 21dB. Last but not least, the test results show that our primary objectives are accomplished.

CHAPTER V

CONCLUSIONS & FUTURE WORK

Billions of wireless devices are predicted to be installed by 2020. Our prototype which is proposed and implemented in this project overcomes the problems associated with the utilizing the spectrum efficiently. The focus of this work is to transmit in real time in TVWS through the USRP device act as a secondary user. This SDR scheme gives the flexibility of quick prototype development for different types of data transmission by using GNU Radio software along with USRP. Overall, the performance of the simulated and implemented our system is relatively well matched in the SNR ranges. This performance matching confirms the validity of the testbed and the applied signal processing techniques in TVWS. This prototype has been tested in the city of Windsor, Canada. It is possible to replicate in any other cites to leverage the utilization of TV gray spaces for communications. The concept of TVWS and the capacity of the GNU Radio have been introduced here. As seen from the implementations of the wireless application on USRP with GNU, it shows that USRP in conjunctions with GNU Radio is a powerful tool for developing and testing wireless systems. A file transfer module has been introduced here with USRP transceiver. We are having objective to use the TVWS for increasing the availability of spectrum for more devices. First spectrum sensing is done for the TV channels band in the city of Windsor. From that information, it has been known that nine channels have identified an idle channel. The real-time data transmission of image, voice, and text have done at the frequency of 525 MHz, for that different types of modulation schemes, for example, GMSK, DPSK, etc. have used. This prototype has the characteristic of having all the radio functions that can be defined and configured based on the situations' demand. In this work two, the USRP uses to communicate with each other.

Moreover, One RTL and Spectrum analyzer use to observe the measures the magnitude of an incoming signal versus frequency, it is helpful to calculate the signal to noise ratio. Besides a python code has been written to see the binary output of the each GRC Block of the GNU Radio and MATLAB code to check the if there is bit error or not (Appendix A & B).

For future work following things are recommended:

- It will be great to run the experiments in the outdoor environment with multiple secondary users in different geographical locations having different frequency spectrum.
- Design a reliable error-free communication scheme prototype by adding forward error coding correction and synchronizing parameters to receiver end.
- This prototype could be employed to exploit the TVWS for other communication applications, for example, public safety service, disaster relief purposes and super Wi-Fi.

Last but not least, someday, TV White space will enable smart cities with connected home devices, sports stadium, shopping centers, municipal areas and more.

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APPENDICES

Appendix A

A.1 Embedded Python Coding

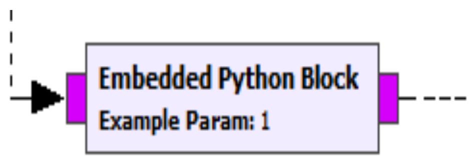


Figure A.1 Embedded Python Block

GNURadio Embedded Python Block (Figure 4.5) helps to write processing blocks in Python and embed them in the GRC flow graph. Embedded Python Block is available in the misc section. After clicking the block, it will open with an example of a document. A Python script has been written to check the output of other GRC block.

The python code has been shown below:

```
"""
Embedded Python Blocks:

Each time this file is saved, GRC will instantiate the first class it finds
to get ports and parameters of GRC block. The arguments to __init__  will
be the parameters. All of them are required to have default values!
```

```
"""
import numpy as np
from gnuradio import gr
class blk(gr.sync_block):  # other base classes are basic_block, decim_block,
interp_block
    """Embedded Python Block example - a simple multiply const"""
    def __init__(self, example_param=1.0):  # only default arguments here
        """arguments to this function show up as parameters in GRC"""
        gr.sync_block.__init__(
            self,
            name='Embedded Python Block',   # will show up in GRC
            in_sig=[np.int8],
            out_sig=[np.int8]
        )
        # if an attribute with the same name as a parameter is found,
        # a callback is registered (properties work, too).
        self.example_param = example_param
    my_buffer=[np.int8]
    def work(self, input_items, output_items):
        """example: multiply with constant"""



      output_items[0][:] = input_items[0] * self.example_param
```

```
    my_buffer[0][:] = output_items[0][:]
    for x in range(len(output_items[0])):
        print(x)
        print("index ", x, "-->", output_items[0][x])
    return len(output_items[0])
```

There are four steps require to write a python block in GNU Radio:

1. Define the data type for the input and output data streams. The default setting is either “complex64” or “float32”. We have changed it to the bytes.
2. Object’s properties are needed to be define. The example provides the “self.example_param”. The parameter can be edited during the execution.
3. It is good to write the code in “work” routine so that it gets called each time the block executes.
4. Lastly, change the name of the block and add the documentation.

A.2 MATLAB Coding for Bit Error Check

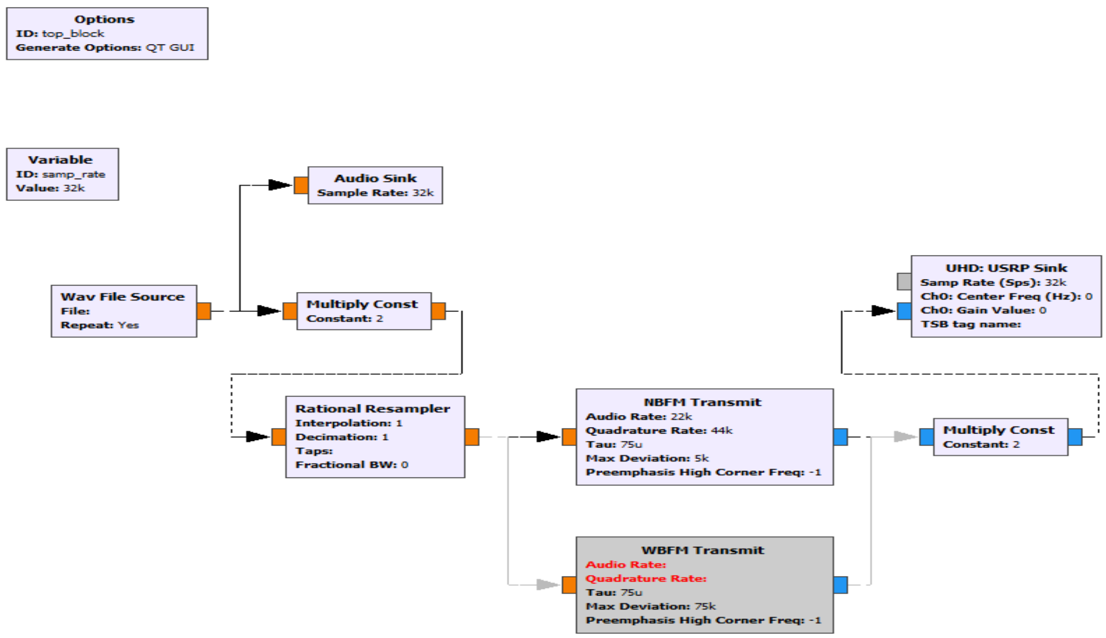
A MATLAB coding has written to countdown the bit error between receive file and original file. The code and output is given below:

```
%% Getting The Signal
Orgfile = fopen('488by1.txt','r');
 Rfile = fopen('recvtxt.txt','r');
```

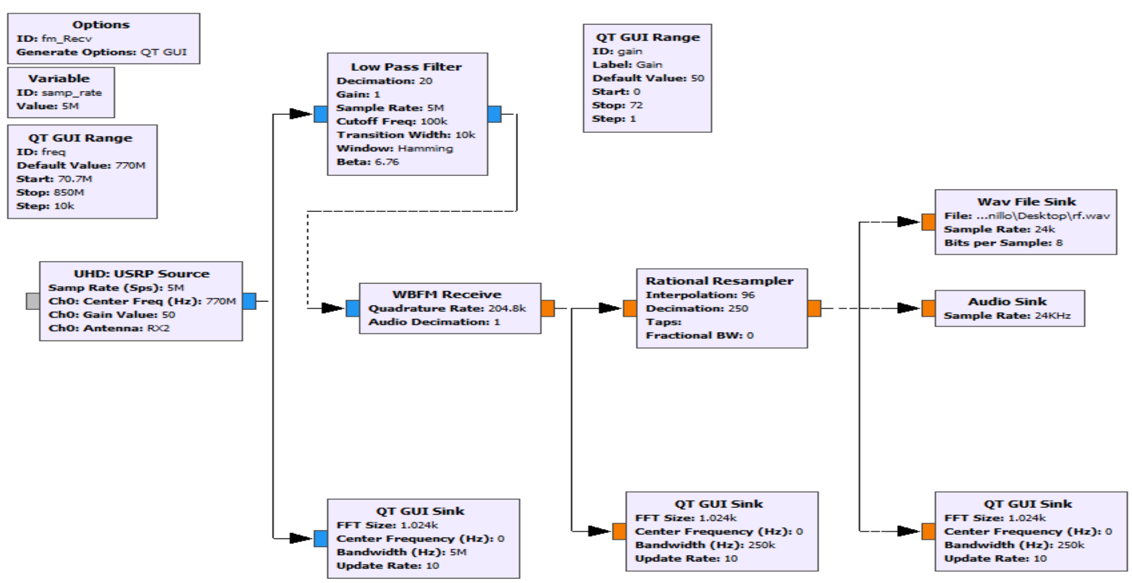
```
%disp(sent) ;
 sent=fread(Orgfile);
 CharData=char(sent);
 received=fread(Rfile);
 CharDatab=char(received);
disp(CharData) ;
sentQBinMat   = de2bi(sent,'left-msb');
sentQBin      = sentQBinMat';
sentQBin      = sentQBin(:)'; % Bit Stream
disp(sentQBin) ;
receivedQBinMat   = de2bi(received,'left-msb');
%disp(receivedQBinMat) ;
receivedQBin      = receivedQBinMat';
receivedQBin      = receivedQBin(:)';
totalBitError = sum(abs( receivedQBin-sentQBin ));
disp(['`Bit Error = ' num2str(totalBitError)]);
```

Appendix B

B.1 The GRC Block Diagram for FM Transmitter and Receiver.



a) FM Transmitter



b) FM Receiver

Figure B.1: The GRC Block Diagram for FM Transmitter and Receiver.

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